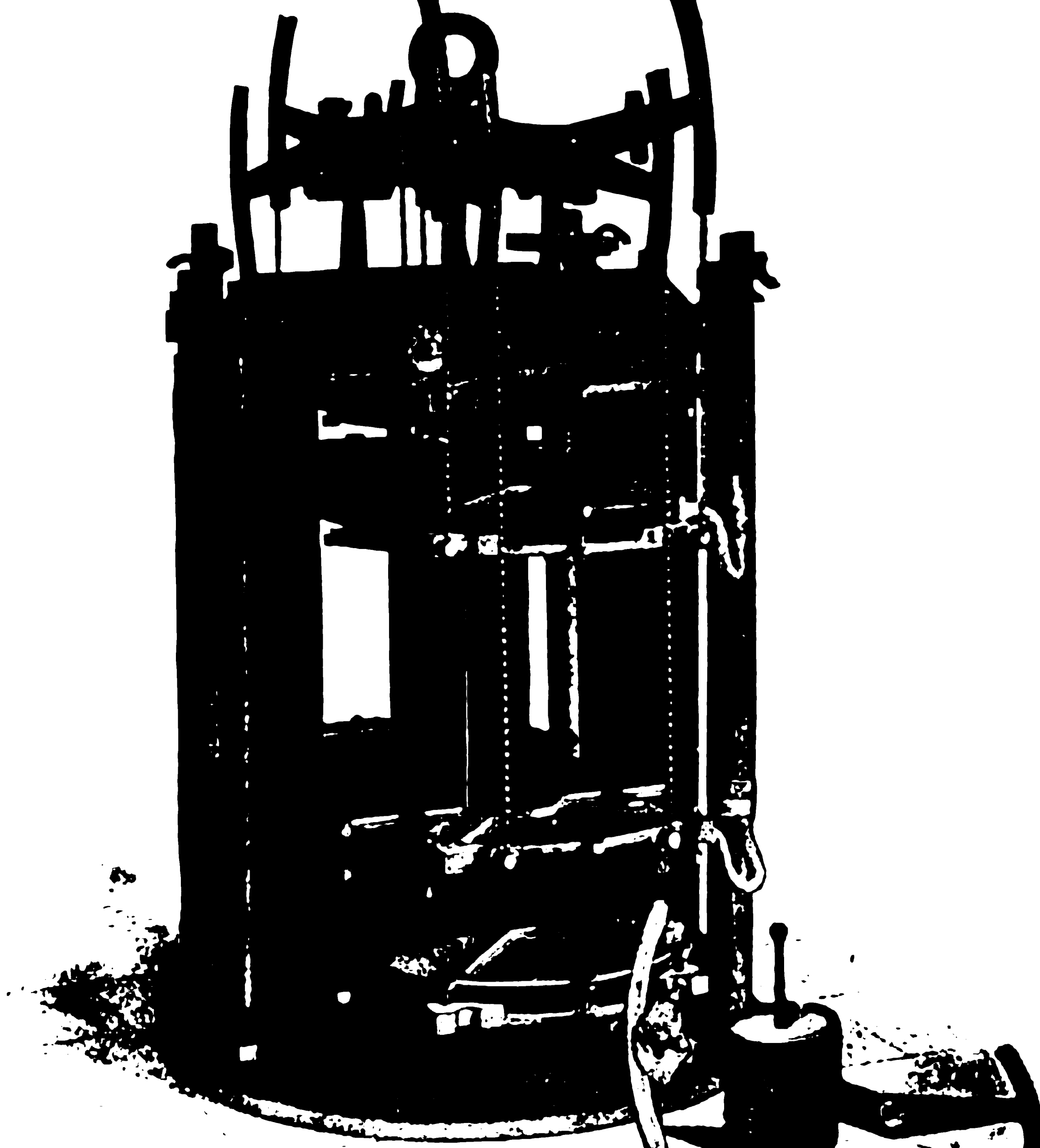

Electric Lighting: Distributing system and lamps

Francis Bacon Crocker

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ELECTRIC LIGHTING

A

PRACTICAL EXPOSITION OF THE ART

FOR THE USE OF

ENGINEERS, STUDENTS, AND OTHERS INTERESTED IN THE INSTALLATION OR OPERATION OF ELECTRICAL PLANTS

VOLUME II.

DISTRIBUTING SYSTEM AND LAMPS

BY

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PREFACE.

In presenting this second volume on the subject of Electric Lighting, attention is called to the fact that it relates to the conductors for transmitting and distributing the current, commonly called the distribution system, to the lamps, the supply of which is the final object of the entire system, and to the various auxiliary devices, such as switches, cut-outs, meters, etc., employed in connection with the same. In short, the present volume covers all parts of electric lighting systems outside of the generating plants, the first volume being devoted to the latter. The properties of conductors and various systems of electrical distribution, including direct current, as well as single and polyphase currents, occupy the first half of the book. Overhead and underground conductors are next discussed, and then arc lamps are treated in considerable detail, since they are important features in electric lighting, and have not been very fully treated in other publications. Interior wiring, incandescent and other forms of lamps, and finally electric meters are given considerable attention. An appendix, containing the National Electrical Code, and another the Report of the Committee on Standardization are included, these being the rules which must, or at least should be, followed in constructing or operating any electrical system. In treating each branch of the subject, the principles have first been given with considerable fullness, being followed by practical examples of the prominent methods and forms of apparatus employed in actual practice. In the space available it has been impossible to go deeply into any subject, but the attempt has been made to cover the important elements and their relation, so that they may be understood and used successfully.

Both volumes are intended as text books for engineering schools and as hand books for practicing engineers, and for that

reason abstruse and detailed matter has been omitted as far as possible.

The National Electrical Code, containing the requirements according to which all electric lighting and other installations should be made, is so important that it is printed in full in Appendix I. The corrections made in December, 1900, were anticipated, and have been incorporated. The Report of the Committee on Standardization of the American Institute of Electrical Engineers being also of fundamental importance, is given in full in Appendix II.

The author is glad to take this opportunity to thank many friends for information and assistance. Messrs. J. W. Lieb, C. W. Rice, and P. Torchio of New York, and Mr. W. S. Barstow of Brooklyn, kindly gave the benefit of their wide experience in connection with electrical distribution. Messrs. Clark and McMullen of New York rendered valuable assistance in connection with overhead and underground conductors. To Mr. Joseph Bijur the author is specially indebted for a great deal contained in the chapters on the electric arc and arc lamps. Mr. John W. Howell, of the General Electric Lamp Works, very kindly read over the proof of the chapter on incandescent lamps, in which subject no one has had greater and more successful experience. Mr. C. S. Aylmer-Small assisted the author in collecting material, in proof-reading, and in other ways. Finally, thanks are due to the General Electric, Westinghouse, and other companies, which have freely given information and illustrations.

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ELECTRIC LIGHTING.

CHAPTER I.

ELECTRICAL DISTRIBUTION.

PHYSICAL PROPERTIES OF CONDUCTORS.

THE distribution of electrical energy from the generating plant to lamps, motors, or other devices involves problems of great scientific and technical interest. It is also a fact that in almost every electrical installation the cost of the distributing conductors is a larger item than that of the generating machinery. This is almost always true of long-distance transmission; and even in an isolated electric-lighting plant the wiring is usually more expensive than the boilers, engines, and dynamos combined.

Substantially the same principles apply to all branches of electrical transmission and distribution, including electric lighting and power, telegraphy, telephony, etc. But the subject has been developed more thoroughly in the case of electric lighting, which requires a more nearly perfect regulation of pressure and current than the other applications.

Measuring Electrical Conductors. — Either the metric system or the ordinary English system of units can be employed to measure the length and cross-section of wires or conductors.* The former system, in spite of its many advantages, is rarely used for this purpose in America or in England; and tables or rules employing it would be practically worthless at the present time, since they must ultimately be used by common workmen. It should be made compulsory before it can be adopted generally. In English measure we can select either the mile, yard, or foot as the unit of length. The first is too large, as it necessitates inconvenient decimal fractions; the yard is often employed in England to measure

* Tables for converting from one system to the other are given in vol. i. pp. 20–22.

electrical conductors, but it is rarely used for that purpose in America, the foot being almost universally adopted as the unit. The size of a wire may be stated either in terms of the numbers of an arbitrary gauge, or the actual diameter in fractions of an inch may be given. Unfortunately the practice of using wire gauges has existed from time immemorial, and results in much confusion because of the great number of different gauges.* This has been overcome to a certain extent in this country by the general adoption of the Brown & Sharpe, or American wire gauge; but this is quite different from the new standard British wire gauge, which is used in England. The American wire gauge will be employed in the present instance, since in this country wires are made and referred to by that gauge very generally; but in many cases it is better to specify the actual diameter or cross-section of the wire. For this purpose the word *mil* has been introduced, being a short name for one thousandth of an inch. That is to say, a wire 100 mils in diameter is one hundred one thousandths, or one tenth of an inch, in diameter. The cross-section of a wire one mil in diameter is called one *circular mil*, being the area of a circle one thousandth of an inch in diameter. Since the cross-section of any other round wire will be proportional to the square of its diameter, it follows that the cross-section in circular mils can be found by multiplying the diameter in mils by itself. We thus avoid the difficulty of converting the cross-section into square measure, which requires the square of the diameter to be multiplied by .7854 or $\pi / 4$. This is an awkward and unnecessary calculation in the case of round wires, it being much simpler and equally definite to measure them in terms of a circular unit. For diameters greater than .46 inch (No. 0000 A.W.G.) it is customary to define the size by giving the diameter in mils or the cross-section in circular mils. For example, a solid round conductor one inch in diameter is designated as 1,000,000 circular mils. The size of a cable made up of a number of strands of wire is given as the sum of the cross-sections of the individual strands. Rectangular conductors are measured in terms of their breadth and thickness in inches or mils, or their cross-section in square mils, which is equal to the product of these two dimensions.

For measuring wires or conductors, a wire gauge or a microm-

* Wheeler's Chart of Wire Gauges, W. J. Johnston Co., N.Y., 1887.

eter may be employed. The former consists of a plate having slots in its edge corresponding in size to the gauge numbers. The latter is usually a screw-micrometer, which measures the diameter or thickness in mils, that is, thousandths of an inch.

Materials for Electrical Conductors. — Copper is the material employed almost universally for electrical conductors, on account of its high conductivity. The slight superiority of silver in this respect is more than offset by its higher density and cost.

There are, however, several metals which are lighter than copper for the same resistance. For example, aluminum has a conductivity about one-half that of copper, and its density is 2.7. Hence, an aluminum wire weighs only $\frac{2.7}{8.89} \times \frac{1.0}{0.5} = 0.607$, or a little more than one-half as much as a copper wire having the same length and resistance. Metallic sodium is only about one-quarter as heavy as copper for equal length and resistance.

Although there are several metals that could be used as electrical conductors which are considerably lighter than copper, it is doubtful if it would be desirable to use them, except in special cases where minimum weight is of particular importance, because their bulk would be so much greater. For example, an aluminum wire must have about twice the cross-section of an equivalent copper wire, and would, therefore, require much more insulating material to cover it, and would be more clumsy for overhead or underground conductors or interior wiring. It may be used, however, for bare conductors, such as 'bus bars, provided its cost is low enough.

In addition to metals such as aluminum, which may be employed for electrical conductors in place of copper, because they are lighter, other metals and alloys are used on account of cheapness or greater strength. The most prominent of these is iron or steel, which until a few years ago was in general use for telegraph and telephone lines. But the most recent practice is to employ copper even for these purposes; it being found that the lower resistance, inductance, and electrostatic capacity (because smaller wires are used) more than make up for the increased first cost. Iron has rarely been utilized as a conductor in electric light, power, or other circuits that carry large currents, because its conductivity is much less, being about one-seventh that of copper. An

iron wire must therefore have seven times the cross-section and $\frac{7 \times 7.8}{8.89} = 6.14$ times the weight of an equivalent copper wire, and would cost about as much.

Nearly all alloys have a considerable lower conductivity than pure copper, so that they are not very generally used, even for overhead conductors. In the latter case, hard-drawn copper wire is generally employed, having a conductivity about 2 to 3 per cent less than that of annealed copper, and a tensile strength about twice as great. The latter is 25,000 to 35,000 lbs. per square inch for soft copper, and 50,000 to 70,000 for hard-drawn, the lower figure being for large sizes (Nos. 0000 and 000) and the higher value for small sizes of wire (Nos. 14 and 16).

Electrical Resistance. — In electrical distribution the most important factor is resistance, from the scientific as well as from the commercial points of view. It entirely determines the flow of a direct current, and largely affects alternating-current circuits also, necessitating the use of large quantities of copper for conductors, the cost of which constitutes the chief item of expense in almost all electrical plants or systems, as already stated.

Resistance appears as a serious difficulty in electrical distribution, producing three objectionable effects. First, it causes a *drop* in voltage, so that the various lamps are not supplied with sufficient pressure or with the same pressure; second, it involves a *loss of energy* and efficiency; and third, it produces *heating* of the conductors, which may destroy the insulation or give rise to danger of fire. Each of these effects will be considered separately later.

The determination of electrical resistance can easily be made either by calculation or by actual measurement. It is not necessary here to explain the many well-known ways of measuring resistance, such as the Wheatstone bridge and the fall of potential methods. These may be found in almost any electrical work. Furthermore, it is the usual practice to determine the electrical resistance of conductors in electric light and power distribution by calculation based upon certain recognized standards. This may be verified by tests of samples of the wire or by measurements made after the conductors are laid.

The Standard Conductivity of Copper. — It is almost universally

customary to express the comparative conductivity of samples of copper in terms of Matthiessen's standard. Unfortunately, Matthiessen gave several values which do not agree exactly. To overcome this difficulty, a committee of the American Institute of Electrical Engineers carefully investigated this question, and recommended the general acceptance of a definite value for Matthiessen's standard. It is possible to obtain copper of greater purity and higher density than that used by Matthiessen, so that a somewhat better conductivity of 102 or even 105 per cent of the standard may be reached. But practically all commercial copper is below Matthiessen's standard.

A complete table was prepared by the committee of the American Institute of Electrical Engineers,* giving the resistance, weight, etc., of the various sizes of wire, for both the American (B. and S.) and Birmingham (Stubs) gauges. This table, for the A. W. G. and covering wires from Nos. 0000 to 18 inclusive, is given on page 8. The resistance of any copper wire at 20 degrees C. or 68 degrees Fahr., according to Matthiessen's standard, may be calculated by the following simple formula: $R = \frac{10.35l}{d^2}$ R being the resistance in international ohms, l the length of the wire in feet, and d its diameter in mils. The latter is easily determined with accuracy by means of the ordinary screw micrometer.

A very simple and convenient rule to remember is the fact that 1,000 feet of No. 10 A. W. G. wire, which is practically one-tenth of an inch in diameter (.1019), has 1 ohm resistance at 20 degrees C. (68 degrees Fahr.), and weighs 31.4 pounds. A wire three sizes larger, that is, No. 7, has almost exactly twice the cross-section and weight per thousand feet, and one-half the resistance. A wire three sizes smaller, that is, No. 13, has one-half the cross-section and weight, and twice the resistance per thousand feet. Three sizes smaller than No. 13, that is, No. 16, has one-fourth the cross-section and weight and four times the resistance of No. 10; and similarly a No. 4 wire has four times the cross-section and weight and one-fourth the resistance of No. 10. This may be carried to the extreme limits of the gauge in either direction, the cross-section doubling with each three numbers. Intermediate sizes may be approximated by interpolation; for example,

* Transactions, vol. x., 1893.

one size larger has about $1\frac{1}{4}$ (1.261) times, and two sizes larger about $1\frac{6}{10}$ (1.59) times the cross-section. The cross-section of the next size smaller is always found by multiplying by .793, and for two sizes smaller by .629.

Temperature Coefficient of Copper. — The effect of variations in temperature upon the conductivity of copper was given by Matthiessen * in the following formula: —

$$C_t = C_o\,(1 - .0038701t + .000009009t^2), \tag{1}$$

in which C_t is the conductivity at any temperature t in Centigrade degrees, and C_o is the conductivity at zero degrees C. This expression is sometimes converted into one for resistance by merely changing signs; but this is incorrect algebraically, since it is necessary to take the reciprocals of both members of the equation. If this is done the following formula is obtained: —

$$R_t = R_o\,(1 + .0038701t + .000005969t^2). \tag{2}$$

This is usually simplified by reducing the number of decimal places, giving the form: —

$$R_t = R_o\,(1 + .00387t + .00000597t^2). \tag{3}$$

In these expressions for resistance, terms containing t^3 and other higher powers of t are neglected, hence, they do not give results agreeing exactly with Matthiessen's original formula (Equa. 1). The correct method is to find the value of the temperature coefficient for conductivity $(1 - .0038701t + .000009009t^2)$, take its reciprocal, which gives the temperature coefficient for resistance, then multiply the resistance at 0° C. by this amount in order to find the resistance at the given temperature t. This is the process by which the figures in the table on page 8 were obtained. But for moderate ranges of temperature the error resulting from the use of Equation 3 is slight, being about $\frac{1}{4}$ of 1 per cent too high at 50° C., and about $\frac{8}{10}$ of 1 per cent too high at 80° C.

Indeed, it is doubtful if any of these somewhat complicated formulæ are actually more correct than the very simply expression, — †

$$R_t = R_o\,(1 + .004t), \tag{4}$$

* *Philosophical Transactions*, 1862.

† *Electrical World*, Feb. 16, 1895.

in which, as before, R_t is the resistance of a copper conductor at the given temperature t, and R_0 is its resistance at 0° C.

Matthiessen found nearly all pure metals to have substantially the same temperature coefficient as copper, the only important exceptions being iron and liquid mercury. The values given for these are somewhat variable, but are about .0045 for the former, and about .0009 for the latter. The temperature coefficients for alloys are less than those of pure metals, being only about one-tenth as great for German silver as for copper.

The resistance in ohms of a soft copper conductor at a given temperature t in Centigrade degrees may be obtained from the following expression:—

$$R_t = \frac{9.586\ (1 + .00387t + .00000597t^2)\ l}{d^2}. \qquad (5)$$

This assumes the ordinary form of Matthiessen's formula (Equa. 3), and gives slightly different results from those set forth in the table on page 8, as already explained.

The very simple expression,—

$$R_t = \frac{9.6\ (1 + .004t)\ l}{d^2} \qquad (6)$$

gives values agreeing exactly with Matthiessen's original formula at 23° C., and not differing by more than two-tenths of one per cent between 0° and 35° C., which covers the ordinary temperature range of conductors used in electrical distribution. At 60° C., which is the usual heating limit allowed in electrical machinery, the results obtained from Equation 6 are three-quarters of one per cent less than those of Matthiessen. This expression is therefore sufficiently accurate for almost any practical calculation.

In fact, the variation in resistance of copper is so great with ordinary changes in temperature that it is rarely possible to predetermine it with great accuracy. The temperature of an overhead line may vary from natural causes enough to alter the resistance about 25 per cent. A further increase due to the heating effect of the current would make a total change of about 40 per cent in resistance. Underground and interior conductors are not subject to such extreme variations in the temperature of their environment, but they often amount to many degrees, particularly for the latter; and the heating effect of the current may be equally

COPPER WIRE TABLE. — Matthiessen's Standard, as Recommended by Am. Inst. of Electrical Engineers. (Transactions October, 1893.)

DIMENSIONS.			WEIGHT.				LENGTH.				RESISTANCE.					
A. W. G. or B. & S.	Diameter.	Area.	Lbs. per Foot.	Lbs. per Ohm.			Feet per Lb.	Feet per Ohm.			Ohms per Lb.			Ohms per Foot.		
	Inches.	Circular mils.		@ 20° C.	@ 50° C.	@ 80° C.		@ 20° C.	@ 50° C.	@ 80° C.	@ 20° C.	@ 50° C.	@ 80° C.	@ 20° C.	@ 50° C.	@ 80° C.
0000	.460	211,600	.6405	13,090	11,720	10,570	1.561	20,440	18,290	16,510	.00007639	.00008535	.00009459	.00004893	.00005467	.00006058
000	.4096	167,800	.5080	8,232	7,369	6,647	1.969	16,210	14,510	13,090	.0001215	.0001357	.0001504	.00006170	.00006893	.00007640
00	.3648	133,100	.4028	5,177	4,634	4,182	2.482	12,850	11,500	10,380	.0001931	.0002158	.0002391	.00007780	.00008692	.00009633
0	.3249	105,500	.3195	3,256	2,914	2,630	3.130	10,190	9,123	8,232	.0003071	.0003431	.0003803	.00009811	.0001096	.0001215
1	.2893	83,690	.2533	2,048	1,833	1,654	3.947	8,083	7,235	6,528	.0004883	.0005456	.0006046	.0001237	.0001382	.0001532
2	.2576	66,370	.2009	1,288	1,153	1,040	4.977	6,410	5,738	5,177	.0007765	.0008675	.0009614	.0001560	.0001743	.0001932
3	.2294	52,630	.1593	810.0	725.0	654.2	6.276	5,084	4,550	4,106	.001235	.001379	.001529	.0001967	.0002198	.0002435
4	.2043	41,740	.1264	509.4	455.9	411.4	7.914	4,031	3,608	3,256	.001963	.002193	.002431	.0002480	.0002771	.0003071
5	.1819	33,100	.1002	320.4	286.7	258.7	9.980	3,197	2,862	2,582	.003122	.003487	.003865	.0003128	.0003495	.0003873
6	.1620	26,250	.07946	201.5	180.3	162.7	12.58	2,535	2,269	2,048	.004963	.005545	.006145	.0003944	.0004406	.0004883
7	.1443	20,820	.06302	126.7	113.4	102.3	15.87	2,011	1,800	1,624	.007892	.008817	.009772	.0004973	.0005556	.0006158
8	.1285	16,510	.04998	79.69	71.33	64.36	20.01	1,595	1,427	1,288	.01255	.01402	.01554	.0006271	.0007007	.0007765
9	.1144	13,090	.03963	50.12	44.86	40.48	25.23	1,265	1,132	1,021	.01995	.02229	.02471	.0007908	.0008835	.0009791
10	.1019	10,380	.03143	31.52	28.21	25.46	31.82	1,003	897.6	809.9	.03173	.03545	.03928	.0009972	.001114	.001235
11	.09074	8,234	.02493	19.82	17.74	16.01	40.12	795.3	711.8	642.3	.05045	.05636	.06246	.001257	.001405	.001557
12	.08081	6,530	.01977	12.47	11.16	10.07	50.59	630.7	564.5	509.4	.08022	.08962	.09932	.001586	.001771	.001963
13	.07196	5,178	.01568	7.840	7.017	6.332	63.79	500.1	447.7	404.0	.1276	.1425	.1579	.001999	.002234	.002476
14	.06408	4,107	.01243	4.931	4.413	3.982	80.44	396.6	355.0	320.3	.2028	.2266	.2511	.002521	.002817	.003122
15	.05707	3,257	.009858	3.101	2.776	2.504	101.4	314.5	281.5	254.0	.3225	3603	.3993	.003179	.003552	.003936
16	.05082	2,583	.007818	1.950	1.746	1.575	127.9	249.4	223.3	201.5	.5128	.5729	.6349	.004009	.004479	.004964
17	.04526	2,048	.006200	1.226	1.098	.9906	161.3	197.8	177.1	159.8	.8153	.9109	1.010	.005055	.005048	.006259
18	.04030	1,624	.004917	.7713	.6904	.6230	203.4	156.9	140.4	126.7	1.296	1.448	1.605	.006374	.007122	.007892

The data from which this table has been computed are as follows: — Matthiessen's standard resistivity, Matthiessen's temperature coefficients, specific gravity of copper = 8.89. Resistance in terms of the international ohm.

Matthiessen's standard 1 metre-gramme of hard drawn copper = 0.1469 B. A. U. @ 0° C. Ratio of resistivity hard to soft copper 1.0226. Resistance of 1 mil foot @ 0° C. = 9.586 international ohm.

1 metre-gramme of soft drawn copper = 0.14365 B. A. U. @ 0° C. One B. A. U. = 0.9866 international ohms. Resistance of 1 mil foot @ 20° C. = 10.35 international ohm.

1 metre-gramme of soft drawn copper = 0.141729 international ohm @ 0° C. Resistance of 1 mil foot @ 50° C. = 11.57 international ohm.

Temperature coefficients of resistance for 20° C., 50° C., and 80° C., 1.07968, 1.20625, and 1.33681 respectively. 1 foot = 0.3048028 metre, 1 pound = 453.59256 grammes.

Although the entries in the table are carried to the fourth significant digit, the computations have been carried to at least five figures. The last digit is therefore correct to within half a unit, representing an arithmetical degree of accuracy of at least one part in two thousand. The diameters of the B. & S. or A. W. G. wires are obtained from the geometrical series in which No. 0000 = 0.4600 inch and No. 36 = 0.005 inch, the nearest fourth significant digit being retained in the areas and diameters so deduced.

It is to be observed that while Matthiessen's standard of resistivity may be permanently recognized, the temperature coefficient of its variation which he introduced, and which is here used, may in future undergo slight revision.

great. Fortunately, however, in electrical transmission or distribution the current does not ordinarily heat wires more than 5 or 10 degrees, the loss of voltage being usually the controlling factor. Under the head of current capacity the rise in temperature of the various kinds of conductors will be discussed later.

In any given case the probable temperature around a conductor and the rise due to the current can be at least approximately determined, so that resistance calculations can be made accordingly.

It is customary to specify in plans and contracts that copper for electrical purposes shall have a conductivity not less than 98 per cent of Matthiessen's standard. In some cases only 96 per cent is required; but it should not be allowed to fall below this limit, as it is perfectly practicable to obtain copper of such quality, and inferior grades would not be enough cheaper to make up for their lower conductivity. Allowance should be made for this fact in calculating the resistance of conductors.

The Drop, or Lost Pressure in Volts. — This is the first effect of resistance in electrical distribution, and is very easily and definitely determined from Ohm's law by changing its ordinary form $I = E/R$ into $E = IR$. This is not only true of the whole circuit, but also applies to any portion or branch of the circuit; and ordinarily it is far simpler and more likely to avoid errors if each part of the circuit is considered separately. In the case of a very complicated electrical system, it would be practically out of the question to treat the circuit as a whole; but it is always possible to divide the system of conductors into separate lengths, in each of which we can determine the current, the resistance, and therefore the fall of potential which takes place. In most practical work the current in amperes is given, since it is usually known how many lamps or how much power are to be supplied. It then becomes necessary to calculate the value of the resistance in order to have the proper value for the drop, the latter being assumed or fixed by the conditions in each case. The common idea that a short conductor of very large diameter has no appreciable resistence is quite fallacious. For example, a bar of copper one foot long and one inch in diameter has about one hundred-thousandth of an ohm resistance. While this may be a negligible amount in most cases, it is always perfectly definite, and is often quite appreciable. Such a rod would carry one thousand amperes with a drop of one hun-

dredth of a volt between its ends, or ten volts per thousand feet, which is by no means insignificant. Bars of this size or larger are often used in practice carrying correspondingly heavy currents; hence it is not safe to ignore resistance, even in the case of very large conductors.

Loss of Energy. — The second objectionable effect which resistance produces in electrical distribution is the loss of energy which it occasions. This loss is absolute, and must always occur whenever a current flows through a resistance. The exact value of this loss is given by the expressions: —

$$\text{Watts lost} = I^2 R = E\,I = \frac{E^2}{R}$$

in which I is the current in amperes, R is the resistance in ohms, and E is the drop or lost pressure in volts, being applicable either to the whole circuit or to any part of it. From one of these expressions the loss of energy can always be ascertained, provided any two of the three quantities are known. These equations give the loss which occurs continuously so long as the current flows; that is, the *rate* of dissipation of energy or the *power* wasted. For a given time t in seconds —

$$\text{Loss of energy (in joules or watt-seconds)} = I^2 Rt = E\,It = \frac{E^2 t}{R}$$

To find the loss of energy in heat units, any of the above values may be multiplied by .24 for calories (gram-degree cent.), or by .00095 to obtain British thermal units (pound-degree Fahr.).

This loss of energy, while quite considerable in almost every electrical system, usually amounting to from 5 to 25 per cent, is rarely the controlling consideration in electric lighting. The *drop*, which has already been considered, and the *heating limit*, which will be discussed later, are usually of more consequence than the mere waste of a small fraction of the total energy, the success or failure of an electric lighting plant being dependent upon keeping them within certain limits.

Economy in Design of Conductors. — In many cases, particularly for long-distance transmission in contradistinction to local distribution, the relation between the first cost of the conductors and the energy lost in them may be a matter of prime importance. This subject was first attacked in 1881 by Lord Kelvin, then Sir

William Thomson, who read before the British Association a paper on "The Economy of Metal Conductors of Electricity," in which he attempted to give a general solution of the problem. The conclusion reached by him, and now known as "Kelvin's Law," may be stated in the following language: *The most economical size of conductor is that for which the annual interest on capital outlay equals the annual cost of energy wasted. In other words, the total annual expenditure for interest on the investment and energy lost on the line is a minimum when these two items are equal to each other.*

The importance of this law has usually been greatly overestimated, but gradually its limitations have been brought out. In 1886 Professors Ayrton and Perry showed, in papers before the Society of Telegraph Engineers and Electricians, that Kelvin's Law applies only in certain cases; and they gave various modifications and extensions of it. Professor George Forbes has also contributed to this subject in his Cantor Lectures of 1885,* in which he showed that the portion of the investment which is not proportional to the cross-section of the conductor should be kept separate, so that the amended law becomes: *The most economical area of conductor is that for which the annual cost of energy wasted is equal to the annual interest on that portion of the capital outlay which is proportional to the area or weight of metal used.* Professor William A. Anthony, in an article on "Economy in Conductors, and the Limitations in the Applicability of Kelvin's Law," † demonstrates that in some cases Kelvin's Law gives absurd results, and may, for example, require that *all of the energy should be wasted in order to secure the highest economy.* This is due to the fact that the minimum *expense* of operation is considered, and the energy *delivered* at the end of the line, which is still more important, is entirely ignored. In fact, a great many laws of this kind can be deduced according to what factors are considered.

Kilgour ‡ and Abbott § give 15 possible combinations of the six variable factors involved in the problem, but state that only 11 of these are likely to be of any practical importance. The six factors and the 11 cases are as follows:

* London *Electrician*, vols. xv. and xvi.

† *Electrical Engineer* (N. Y.), Oct. 31, 1894.

‡ *Electrical Distribution*, London, 1893, p. 115.

§ *Electrical Transmission of Energy*, N. Y., 1895, p. 457.

$V =$ the pressure at the receiving end of the conductor;
$v =$ the pressure at the delivering end of the conductor;
$W =$ the power given to the receiving end of the conductor;
$w =$ the power obtained at the delivering end of the conductor;
$I =$ the current in amperes, and
$S =$ the cross-section of the conductor.

CASE NO.	GIVEN.	REQUIRED.	CASE NO.	GIVEN.	REQUIRED.
1	$V, v.$	$I, W, w, S.$	7	$v, S.$	$V, I, W, w.$
2	$V, I.$	$v, W, w, S.$	8	$I, S.$	$V, v, W, w.$
3	$V, w.$	$v, I, W, S.$	9	$W, w.$	$V, v, I, S.$
4	$V, S.$	$v, I, W, w.$	10	$W, S.$	$V, v, I, w.$
5	$v, I.$	$V, W, w, S.$	11	$w, S.$	$V, v, I, W.$
6	$v, W.$	$V, I, w, S.$			

This is a far more complete treatment of the question than that originally given, Kelvin's Law being only one (No. 5) of these 11 different cases. But any of these solutions of the problem is of somewhat doubtful practical value; and it is probably true that Kelvin's Law, or any modification or extension of it that has yet been brought out, has done more harm than good in electrical engineering. It gives a false confidence in the results of calculations which may be totally at variance with real commercial economy. The reason for this difficulty lies chiefly in the fact that the actual costs of some of the items cannot be expressed, even approximately, as mathematical functions. Furthermore, various incidental factors and particular conditions arise, such as the available sizes of machines, which render a general solution of this problem of questionable value in the actual cases which are found in practical work.

It is a common mistake to forget that the interest and depreciation on the investment is a fixed and irretrievable expense, while the energy lost on the conductor depends upon the power transmitted. When the plant is lightly loaded, or is shut down entirely, owing to hard times, strikes, etc., the fixed charges run on as usual, but the energy loss is greatly reduced, or stopped altogether. Hence it is not wise to lay the full amount of copper corresponding to the maximum or even ordinary demands, as there is no control over the investment after it is once made, whereas the energy loss adjusts itself to the working conditions.

Probably the safest, as well as the quickest, method to arrive at a correct result would be to obtain a general solution of the

problem by means of some form of Kelvin's Law; then this result should be carefully checked by assuming a larger and also a smaller wire, and estimating the economy that would be secured if they were substituted for the size of wire obtained by the calculation. The difficulties of determining the various items of expense are greatly reduced by assuming a certain size of wire, and the several factors that are almost impossible to cover by a general formula, immediately become definite. Scientific and rational methods should always be preferred to empirical ones; but every experienced engineer will admit that when complicated questions of cost arise it is unwise to rely entirely upon general formulæ, which are almost necessarily abstract and incomplete. The attempt to force science beyond its legitimate limits has done great injury to many industrial enterprises as well as to science itself.

Specific examples of this problem will be considered later in the case of constant-current arc-lighting circuits and feeders for constant potential systems.

Current-Carrying Capacity of Conductors. — The third objectionable effect of resistance in electrical distribution is the heating which it causes. The production of heat in an electrical conductor has already been stated in terms of the various quantities involved. This heat is an absolutely definite and unavoidable result of the flow of the current. Its effect is to raise the temperature of the conductor, and this rise continues until the rate at which heat is lost equals the rate at which it is generated; then the temperature becomes constant. It is obvious, therefore, that any electrical conductor is only capable of carrying a certain current with a given elevation of temperature, and in practical work the allowable temperature is limited by considerations of injury to insulation, danger of fire, etc. No exact general rule for current capacity can be given, as much depends upon the conditions in each case. But, since a wide margin must be allowed between the danger point and the permissible current capacity, it is possible to establish rules which are somewhat arbitrary, but sufficiently safe in almost any case. This is practicably the basis upon which tables are made giving the current that it is allowable for any size of wire to carry. These tables are partly based upon general experience, and partly the results of experiment and calculation.

The first rule of this kind originated with Lord Kelvin, and

was adopted by the Board of Trade (London). It stated that the current density in copper conductors should not exceed 1,000 amperes per square inch of cross section.

Professor George Forbes discussed this problem in a paper read before the Institution of Electrical Engineers (London) in March, 1884, and showed that the Board of Trade rule was hardly safe for very large conductors, and gave an unnecessarily large margin for small wires. This fact is very evident when it is considered that the current at a given density and also the heating increase in proportion to the square of the diameter of a wire, while the heat-dissipating surface only increases as the diameter.

Dr. A. E. Kennelly has given the results of his investigations in two papers before the Association of Edison Illuminating Companies, Aug. 13, 1889, and Aug. 11, 1893.* He determined by calculation and experiment the heating of conductors submerged in water, buried in the earth, inclosed in wooden molding, and suspended in air.

It is found that there is not such a great difference between the heating effects under these various conditions. An insulated cable in water is the simplest case; since the rise in temperature of the conductor depends merely upon the thermal resistance of the insulation, the outer surface (or sheathing) of the latter being kept at a constant temperature by the water. An underground conductor only differs from the foregoing in the fact that its sheathing may rise in temperature because heat is not taken from it rapidly enough by the surrounding soil or conduit. In other words, the thermal resistance of the conduit and soil is added to that of the insulating covering. For underground conductors in iron pipe conduits laid in cement, the temperature elevation due to this cause would be small, probably not more than 10 or 20 per cent greater than that of the same cables submerged in water. The heating of conductors in wooden or even earthenware conduits would be considerably greater, and in the case of the former might be considered to be the same as for those placed in wooden panels or molding, the rules for which will be given later. Insulated wires suspended in air are more highly heated than similar submarine or most underground conductors, for the reason that the thermal losses by radiation and convection through the air are

* Electrical World, Nov. 23 and 30, 1889 and Sept. 2 and 9, 1893.

less than those through water and solid bodies, except those which are very poor conductors of heat, such as wood. For similar reasons the temperature rise of a bare wire in air is usually greater than that of the same wire covered with insulating material. The effect of the latter is to increase the surface from which heat is radiated and carried away by convection. In most cases a considerable increase in the temperature of a bare wire is not objectionable except so far as it represents loss of energy. The real limitation to the heating of electrical conductors is the point at which their insulation is likely to be injured.

The following are standard tables, giving the maximum current-carrying capacity of different sizes of insulated copper conductors :

TABLES OF CURRENT-CARRYING CAPACITY.

	TABLE 1.	TABLE 2.	TABLE 3.
A. W. G.	AMPERES.	AMPERES.	AMPERES.
18	3	3	5
16	5	6	8
14	10	12	16
12	15	17	23
10	20	24	32
8	25	33	46
6	35	46	65
5	45	54	77
4	50	65	92
3	60	76	110
2	70	90	131
1	85	107	156
0	100	127	185
00	120	150	220
000	145	177	262
0000	175	210	312

	TABLE 2.	TABLE 3.
CIRCULAR MILLS.	AMPERES.	AMPERES.
200,000	200	300
300,000	270	400
400,000	330	500
500,000	390	590
600,000	450	680
700,000	500	760
800,000	550	840
900,000	600	920
1,000,000	650	1,000
1,100,000	690	1,080
1,200,000	730	1,150
1,300,000	770	1,220
1,400,000	810	1,290
1,500,000	850	1,360
1,600,000	890	1,430
1,700,000	930	1,490
1,800,000	970	1,550
1,900,000	1,010	1,610
2,000,000	1,050	1,670

Table No. 1 is based upon Kennelly's experiments, and is intended to allow a rise in temperature of 75° F. for twice the current specified, thus giving an ample factor of safety. The normal current would only raise the temperature 18$\frac{3}{4}$° F., since the heating effect is proportional to the square of the current. The National Electrical Code permits a current density 20 to 25 per cent greater than the foregoing, the figures being given in Table 2.

This would give a temperature elevation of 27° to 30° F., and still allows a considerable increase (about 60 per cent) in current above the rated value without injurious effects. This applies to rubber-covered wires, which should never be heated above 150° F., and should have a normal working temperature considerably below this limit, in order to have a margin for safety. Table 3 permits a still greater current density, and is used for wires with "weather proof" insulation, which is not so susceptible as rubber to injury by heat.

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CHAPTER II.

SERIES SYSTEMS OF ELECTRICAL DISTRIBUTION.

The various systems of electrical transmission and distribution are classified in the following table. They are especially selected with reference to their use in electric lighting; but they include those employed for power transmission and other electrical purposes, the same principles and methods being generally applicable.

SYSTEMS OF ELECTRICAL DISTRIBUTION.

SERIES SYSTEMS.

Constant Current. Voltage usually varied. Direct Current.

1. Series arc lighting.
   Usually operated at about 10 amperes and 50 volts per lamp.
2. Series incandescent lighting.
   About 10 amperes and 10 to 30 volts per lamp (about 3 candle-power per volt).
3. Series incandescent lighting ("Municipal systems").
   Three to 3.5 amperes and 20 to 50 volts per lamp (1 volt per candle-power).
4. Series-parallel incandescent lighting.
   Similar to No. 2, but single lamps replaced by groups in parallel.
5. Direct current converter systems for incandescent or arc lighting.
   Motor-dynamos in series, lamps supplied by secondary circuits.

Alternating Current.

6, 7, 8, 9, and 10. Alternating current systems corresponding to Nos. 1, 2, 3, 4, and 5.

PARALLEL SYSTEMS.

Constant Potential. Current varies with number of lamps. Direct Current.

11. Two-wire incandescent and arc lighting (about 110 or 220 volts).
12. Three-wire incandescent and arc lighting (about 220 or 440 volts).
13. Five-wire incandescent and arc lighting (about 440 volts).
14. Two-wire with motor converters in parallel (primary 1,000 to 5,000 volts).

Single Phase Alternating Current.

15. Low tension incandescent and arc lighting without transformers.
    This corresponds to No. 11. Other alternating current systems similar to Nos. 12, 13, and 14 have not been introduced.
16. High-tension incandescent and arc lighting with transformers.
    Primary circuit 1,000 to 5,000 volts, two- and three-wire secondary circuits at about 50, 100, or 200 volts.
17. Very high tension systems with step-up and step-down transformers.
    Long distance transmission circuit 5,000 to 25,000 volts.

Polyphase Alternating Current.

18. Two-phase system.
19. Three-phase system.
20. Monocyclic system.

For the sake of completeness, the above table includes almost every possible system of electrical distribution, but many of them are unimportant or entirely obsolete at the present time. The systems which are now more or less generally used are Nos. 1, 11, 12, 13, 14, 16, 17, 18, 19, and 20. The last three are primarily intended to operate motors, but are also employed in many cases for electric lighting.

SERIES SYSTEMS OF DISTRIBUTION.

The simplest arrangement of lamps or other devices to be supplied with electrical energy is a series system in which the current from the + terminal of the dynamo, *D*, passes first through

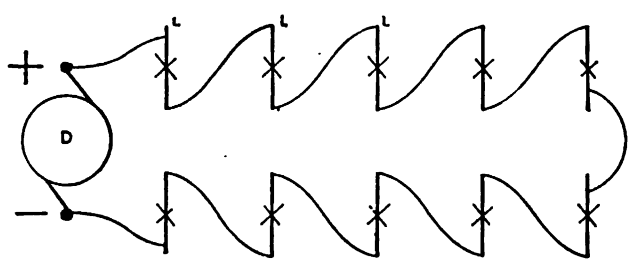


Fig. 1. Series Arc Circuit.

one lamp, *L*, and then through another, and so on, finally returning to the — terminal of the dynamo, as shown in Fig. 1. In such cases the current is usually constant, hence the expression *constant current* is practically synonymous with *series* in electrical distribu-

tion. The term *high tension* also applies, since the voltage usually employed is high, being equal to the sum of the pressures consumed in all of the lamps on the circuit. For example, sixty lamps are commonly placed upon a single arc-lighting circuit; and since each lamp (open arc) requires about fifty volts, it follows that the total pressure approximates 3,000 volts. The problem of designing or studying series circuits is not difficult, the path of the current being usually simple, and the current constant throughout the circuit. This last statement is only true, however, if the leakage of current is insignificant, which is generally the case in electric light and power distribution.

Distribution of Potential on Series Systems. — The potential on a series system falls throughout the circuit in direct proportion to the resistance. That is, $E=IR$, the difference of potential E in volts between any two points being equal to the product of the current I in amperes and the resistance R in ohms included between them. This simple fact completely covers any possible problem that can arise in connection with a series system, provided a direct current is used, and is easily applied in almost any

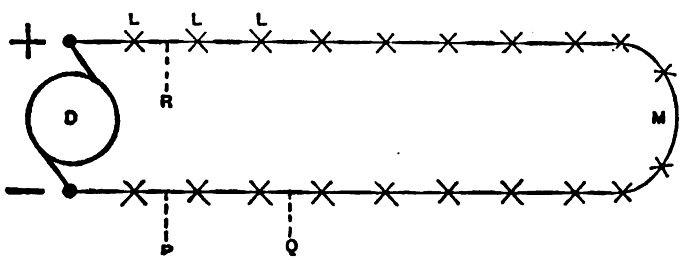


Fig. 2. Distribution of Potential on Series System.

case. In Fig. 2 an arc-lighting system is represented, D being the dynamo and L, L, L, the lamps, connected in series. The total difference of potential generated by the dynamo is assumed to be 1,000 volts, measured between the two brushes marked + and —. This potential falls as the current traverses the circuit, fifty volts being consumed by each of the twenty lamps. This is made up of forty-five volts actually used in the lamp itself, and a drop of five volts on the conductor between two lamps. That is, the drop on the line wire is usually about 10 per cent of the total *E.M.F.* The relative potential of the various points on the circuit is easily

found. For exampie, between the + brush and the middle point M of the circuit, there is a difference of potential of 500 volts, and the same amount between the middle point and the — brush. Similarly any two points on the circuit will have a difference of potential equal to fifty volts, multiplied by the number of lamps included between them.

Personal Danger from Series Circuits. — If a man standing on the ground touches a very highly insulated circuit, only a very slight current will pass through his body; but if the insulation is low or any defect exists at any particular point, then a considerable current may flow through his body. In Fig. 2 the line is supposed to have a ground connection at the point P, due to a defect in the insulation. This will cause the potential of the circuit to be zero at that point; consequently a man may stand on the ground, and touch the line at that point with perfect impunity. If he touches the wire at point Q he will receive a barely perceptible shock, due to 100 volts, since there are two lamps between that point and the ground connection; but if the circuit be touched at the point R, the difference of potential between it and the ground connection being $18 \times 50 = 900$ volts, will produce a dangerous, or perhaps fatal, current. When the defect in the insulation does not amount to what is called "dead ground," but has a resistance, for example, of 1,000 ohms, then a man touching the wire at the point R will receive a shock due to 900 volts as before; but the resistance of the ground connection, which is 1,000 ohms, will be in series with his body. Consequently the current will be less; and, assuming the resistance of his body to be 1,000 ohms, the current will be one-half as great as in the first case. If the ground connection has a resistance of 8,000 ohms, the current through the body would be $\frac{900}{8,000 + 1,000} = \frac{1}{10}$ of an ampere, which is not dangerous.

We may sum up these various cases as follows: —

1. A very highly insulated direct-current electrical circuit may be touched at any one point without danger by a man standing on or in connection with the ground.

2. If a ground connection exists on a series electrical circuit, the danger of touching the circuit increases directly with the resistance between the ground connection and the point of contact.

3. The resistance of the ground connection is in series witb

the body of any one connected with the ground and touching the wire at some other point.

4. It is never safe, however, to assume the insulation to be perfect, or that a ground connection exists at some particular point, or that it has a high resistance. The circuit should always be treated as if the most dangerous possible conditions existed.

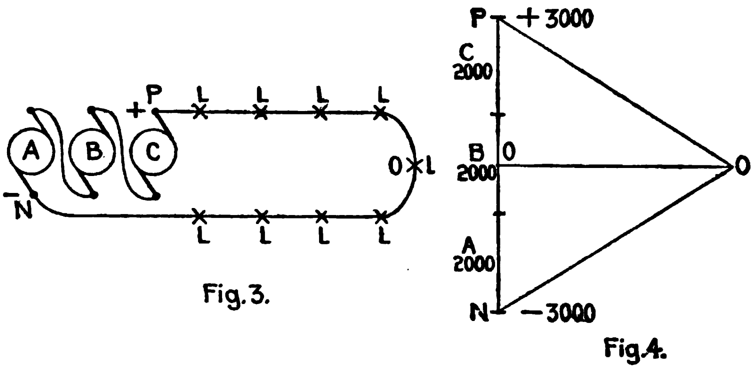
Regulation of Series Systems. — The condition required on series circuits is usually the maintenance of a *constant current.* This is accomplished by designing the dynamo so that it will automatically generate a nearly constant current. The various dynamos used in series arc-lighting, such as the Brush, Thomson-Houston, and Wood machines, are well-known examples of this type of generator. They are provided with regulating devices, which either shift the brushes or vary the strength of the field, or both, in order to keep the current at a constant value. In addition to these special regulators, such machines are so designed that they have considerable self-induction, resistance, and armature-reaction, all of which tend to prevent the current from rising to a high value, even when the machine is short-circuited.*

Series Arc-Lighting System. — The general arrangement of the apparatus and circuit is represented in Fig. 1. The dynamo and lamps may be selected from the various well-known and thoroughly successful forms of constant-current arc-lighting apparatus. The determination of the proper size of wire is not very difficult. General custom and considerations of strength require that no wire smaller than No. 8, A. W. G., should be used. Similarly it would not usually be necessary to employ a conductor larger than No. 4, because the potential being high, and the current small, the loss of energy is not great, even in a wire several miles in length. To take a specific case, let us assume a circuit five miles long, supplying 80 arc lamps, the potential being 4,000 volts and the current 10 amperes. If No. 6 wire is used, the resistance would be 2.1 ohms per mile, or 10.5 ohms for the whole line. This involves a drop of 105 volts and a loss of energy of 1,050 watts, which is only 2.63 per cent; consequently it is evident that the use of a little larger or a little smaller wire would not seriously affect the economical working of such a line. The substitution of No. 3 for No. 6 wire would save one-half the loss of energy, the cross-

* For a description of such machines see Vol. I., p. 330.

section and weight being twice as great, and the cost of the insulated conductor would be nearly doubled. With No. 6 wire the total weight of copper would be 2,098 pounds, and the cost of the wire (insulated) would be about $500. It is doubtful if it would be wise to invest an additional $500 in order to use No. 3 wire and save one-half the energy or 525 watts.

The New Brush Arc-Lighting System is an interesting case of series distribution. In the original type of Brush dynamo the armature is provided with two or more separate open-coil windings, connected to a corresponding number of commutators. The circuit leads through these windings in series, so that the construction may be regarded as equivalent to several armatures in series.



Figs. 3 and 4. Original Arrangement of Brush Arc Lighting System.

This arrangement is represented diagrammatically in Fig. 3, in which *A*, *B*, and *C* are three commutators connected in series with each other and with the line that supplies a number of lamps, *L*, *L*, etc., in the usual manner. Assuming each armature winding to generate 2,000 volts, the total *E.M.F.* of the machine will be 6,000 volts. The distribution of potential in this case is shown in Fig. 4, the + brush of *C* being + 3,000 volts, and the – brush of *A* being – 3,000 volts, with respect to the potential of the earth, which is represented by the zero line *OO*. The fall of potential through the circuit is indicated by the inclined lines, *P O* and *O N*, the total amount being 6,000 volts, and the middle point being zero. This assumes an ideal case with a uniform distribution of conductor resistance and insulation resistance, but would

be approximately true for a practical case in which the system was in good condition. If the insulation of some portion of the circuit became poor, it would tend to make the potential at that point approach zero, producing a corresponding change in the rest of the circuit. For example, a ground connection at the negative terminal *N* would bring that point to zero, and the positive terminal *P* would then become + 6,000 volts, as represented in Fig. 5.

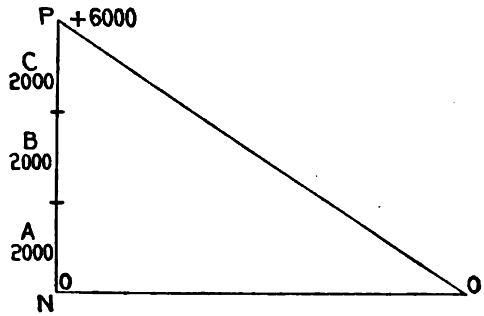


Fig. 5. Distribution of Potential with Grounded Terminal.

The new Brush system, illustrated in Fig. 6, differs from the old in the fact that the lamps, *L, L,* are inserted in the circuit between the commutators *A, B,* and *C,* in which case the line consists of three loops. With this arrangement, the *E.M.F.* generated by each of the three armature windings is consumed by the lamps

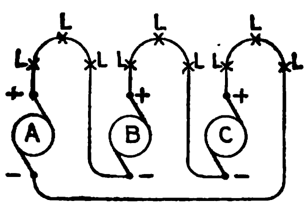


Fig. 6.

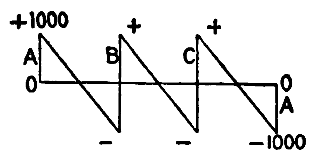


Fig. 7.

Figs. 6 and 7. New Arrangement of Brush Arc Lighting System.

between it and the next armature winding, so that the potential does not rise above + 1,000 volts, or fall below − 1,000 volts, in the ideal case represented in Fig. 7. Even if the circuit becomes grounded at any point, the potential will nowhere exceed 2,000 volts, and the maximum difference of potential existing between any portions of the circuit will not be greater than this amount. A voltmeter connected across from the − brush of *B* to the + brush of *C* would only indicate 2,000 volts, in spite of the fact that the *E.M.F.* generated between those points is 4,000 volts, the

remaining 2,000 volts being used in the lamps between *B* and *C*. This reduction or subdivision of the total *E.M.F.* is the advantage of this system, and avoids the dangers involved in the use of the ordinary types of machine for supplying a large number (50 to 200) of arc lamps in series. On the other hand, it is necessary to arrange the line in several loops instead of having one long circuit. In Fig. 6, for example, there would be six wires running out from the station, while Fig. 3 would only require two. Nevertheless, the former plan may be preferable to the operation of three separate dynamos, which would be less efficient, occupy more space, and demand more attention than a single large machine.

If desired, the number of lamps on any loop may be increased or decreased, since the current is kept constant by a regulator on the dynamo; and it is quite immaterial where the resistance is introduced in a series circuit. In fact, any or all of the lamps may be cut out, or they may be put upon two loops and none on the third, or the full load may be placed on a single loop, in which case the arrangement reduces to the ordinary one shown in Fig. 3. When the number of lamps on any loop is augmented or diminished, the potential difference between its terminals varies in direct proportion, so that two-thirds of the lamps on one loop would require a *P.D.* of 4,000 volts between the brushes to which it is connected. This gives great flexibility to the system, and provided the lamps are not very unequally divided, the pressure is not excessive on any one loop. It should be noted that in either the old or the new system, the full *E.M.F.* of 6,000 volts would be found to exist if the circuit be opened at any point. Indeed, the *P.D.* would tend to rise momentarily considerably above the normal voltage.*

Series Incandescent Lamps on Arc Circuits. — Several forms of incandescent lamps have been designed and manufactured for use on the regular 10-ampere arc circuits. These consist of lamps similar in general principle and construction to those used for constant potential, parallel distribution, but containing a shorter filament of larger cross-section that is sufficiently heavy to carry the full current of 10 amperes.

The most important consideration is that of maintaining the continuity of the circuit when the filament of any lamp happens to break, which might occur at any time. This may be accomplished

* Vol. I., p. 331.

by some form of cut-out, which short-circuits the lamp when the filament is broken. One type of this device is called a "film cut-out," and consists of a thin sheet, *F*, of paper or other material interposed between the points *P* and *P* connected to the conductors *A* and *B* which enter and leave the lamp, as represented in Fig. 8. This film obliges the current to pass through the lamp so long as the filament is intact; but when the latter breaks, the difference of potential rises from its ordinary value of 10 or 20 volts to the full *E.M.F.* of the circuit, which is usually several thousand volts. This high pressure is sufficient to puncture the film, allowing the current to pass directly across between the points *P* and *P*, thus short-circuiting the lamp and re-establishing the continuity of the circuit.

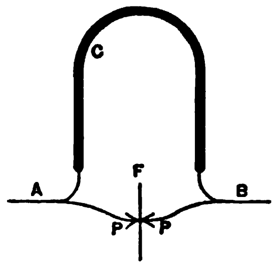


Fig. 8.
Film Cut-Out for Series Incandescent Lamp.

In some cases a small automatic switch is employed, which is caused to close and short-circuit the lamp by means of a magnet connected across as a shunt between the leads of the lamp. The coils of this magnet are of high resistance, and carry little current until the filament is broken, when the full current is thrown through them, causing the switch to close.

"Municipal" Series Incandescent Lighting Systems. — These are similar to the preceding; but instead of operating with a standard arc-lighting current of 10 amperes, they are usually designed for about 3 or 3.5 amperes. This gives a filament of sufficient length and cross-section to be durable, and yet does not require excessively large leading-in wires. The lamps are made of various sizes, requiring about one volt per candle-power. The practice with this system is to feed the circuit with a constant potential, usually from 500 to 1,000 volts, several of such circuits being ordinarily operated in parallel by the same dynamo, *D*, as represented in Fig. 9. This arrangement is therefore a *parallel-series system.* When the filament of a lamp breaks, and it is automatically cut out of the circuit, the current increases in strength, since the total resistance is reduced, the potential remaining constant. This increase of current is indicated by an ampere meter, or current indicator *A* placed in each circuit, and is corrected and brought back

to its normal value by switching in an extra or "relief" lamp L_1, at the station. This is usually done by an attendant who is kept on duty to watch the various circuits. The system is rather a crude one, and is rarely used except for street-lighting in place of arc lights where the more powerful light of the latter is not required. Either the direct or alternating current is applicable to this method of distribution, and both have been used. The current capacity of the dynamo must be sufficient to supply the various circuits in parallel. In the case shown (Fig. 9), the current required would be 15 amperes, since there are 5 rows of lamps, each taking 3 amperes. With 10 lamps of 50-candle-power and 50 volts in series, the dynamo should operate at a constant potential of 500 volts. A shunt or compound wound direct current machine, or a separately excited or composite alternator, would be suitable for the purpose.

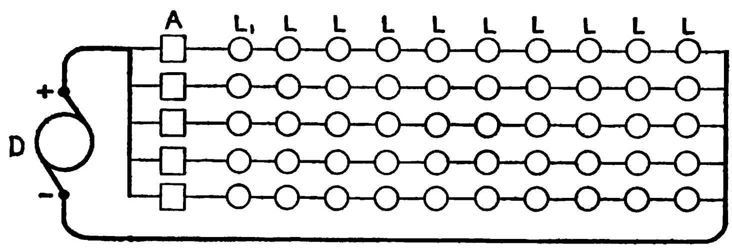


Fig. 9. Parallel-Series System of Distribution.

In the case of the compound or composite machines they should simply give an absolutely constant potential, since the number of lamps, and therefore the drop, on each circuit is constant.

Series-Parallel Incandescent Lighting Systems may be arranged in the manner indicated in Fig. 10. Several lamps are arranged in parallel to form a group, and a number of such sets are connected in series, as shown. It is not necessary for the groups to be identical, provided they are all adapted to take the same current in amperes, which should be kept constant, and provided the lamps of each set agree in voltage. For example, on the ordinary 10-ampere arc circuit, one group might consist of 5 lamps, each requiring 50 volts and 2 amperes; the next might be composed of 10 lamps, each taking 100 volts and 1 ampere, and so on.

Such groups have been used directly on the ordinary series arc-lighting circuits (constant current), like the series incandescent

lamps described on page 24. The former arrangement is even less practical than the latter, and is also inferior to the "municipal" system, since a lamp which breaks or burns out cannot be either short-circuited or compensated for by adding a lamp in the station. To provide for this contingency, which is likely to be of frequent occurrence, a local device is required for each group, which will either connect a new lamp whenever any one of the

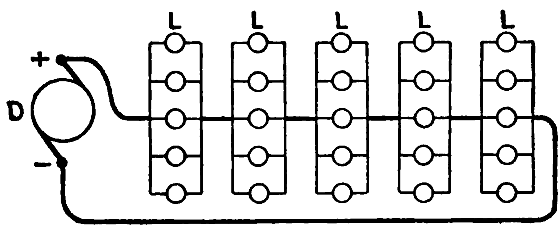


Fig. 10. Series-Parallel System of Distribution.

lamps fails, or short-circuit the entire group. This is such a complicated and unreliable arrangement that the system is not a very practical one.

Alternating Current Series Systems. — Each of the direct current series systems that have been described has, or at least might have, a counterpart alternating current system. The general arrangement and method of operation would remain substantially the same; but as the phenomena of alternating currents differ in some respects from those of direct currents, the discussion of such systems will be given in the chapters on Alternating Current Distribution.

CHAPTER III.

PARALLEL SYSTEMS OF ELECTRICAL DISTRIBUTION.

In contradistinction to the series connection of lamps or other devices to be supplied with electrical energy, the other common method of distribution is the *parallel* or *multiple arc* arrangement represented in Fig. 11. Assuming that four lamps, each taking one ampere, are to be fed, the current generated by the dynamo *D* should be 4 amperes, which divides at the point where the first lamp is connected, and 1 ampere flows through it. The remaining 3 amperes pass on to the next lamp, and so on. The current supplied by the source should be equal to the sum of the amperes

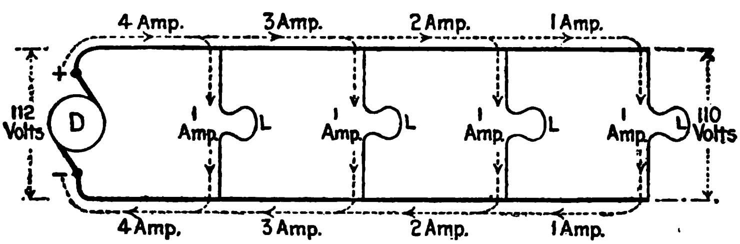


Fig. 11. Principle of Parallel Distribution.

required by all of the lamps or other devices that are connected at any given time. The voltage should be as nearly constant as possible; hence the system is designated as *constant potential*, but this is only approximately true. In the case illustrated, the dynamo generates 112 volts, which is slightly reduced by the resistance of the wires until it falls to 110 volts at the last lamp.

Parallel systems are far more important in electrical distribution than series systems; since practically all incandescent lamps, a large proportion of arc lamps, and nearly all electric motors, are supplied by them. Constant potential circuits are usually more complicated than the simple series systems, there being only a

single path for the current in the latter case, while with parallel connections there are a number of branching paths. Furthermore, the maintenance of a uniform voltage over a large district is exceedingly difficult. The "drop" or loss of voltage, due to the resistance of conductors, which has already been discussed on page 9, is particularly objectionable in incandescent lighting, since the slightest decrease of potential produces a very considerable diminution of light. For example, the candle-power of an ordinary lamp is reduced from 16 to 15, which is more than 6 per cent, when the pressure falls from 110 to 109 volts, or less than 1 per cent. Such a very small variation in pressure would hardly be appreciable in any other practical work, such as steam or gas distribution.

The drop in pressure produces three different effects in the lamps or other devices supplied by parallel circuits: —

(1) All of the lamps receive a lower voltage than that generated by the source of electrical energy.

(2) Some lamps may be supplied with a lower pressure than others.

(3) The potential at some lamps may vary when others are thrown on or off the same circuit.

The least harmful of these effects is the first, which merely requires the generator to be run at a little higher voltage, and does not necessarily involve any difference between the candle-power of the lamps, since the drop may be made substantially the same for all of them by some of the methods described later.

On the other hand, *variations* in the candle-power of lamps, due to either of the last two effects, are extremely objectionable and difficult to overcome. In order to study these problems let us take a specific case, and assume that 100 incandescent lamps are to be supplied with electric current. They are supposed to be divided into five groups of 20 lamps each; each lamp requires a current of 110 volts and one-half ampere, and gives 16 candle-power; therefore one group takes 10 amperes, the total current being 50 amperes. The members of each group of lamps are connected in parallel in the usual manner, but will be indicated by a single line in the following diagrams in order to avoid confusion. These groups are assumed to be 200 feet apart in a straight line, making a total distance of 800 feet between the extreme groups, as shown

in Fig. 13. The five groups of lamps represented by the light vertical lines are connected together by two conductors, which are shown as heavy horizontal lines. These conductors correspond to the so-called *mains* in electrical distribution systems, to which are connected the *leads* or small branch wires actually supplying the

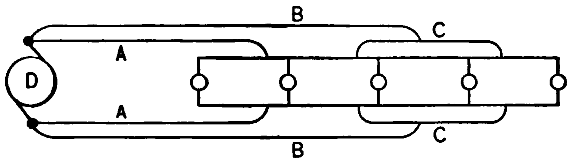


Fig. 12. Arrangement of Feeders and Mains.

lamps. The mains receive their current through *feeders, AA* and *BB*, which connect them with the generating plant *D*, as represented in Fig. 12. As a general rule no lamps are connected directly to the feeders. The celebrated "Feeder and Main" patent of Edison * covered this arrangement of electrical conductors.

In the first case, represented in Fig. 13, the mains are supposed to be fed at one end, the feeding-points being represented by short vertical lines marked + and – respectively. The mains are assumed to consist of No. 0000 wire, A. W. G., which would weigh 1,025 pounds for 1,600 feet required. Each section of the mains consists of 200 feet of No. 0000 wire, and has a resistance of about

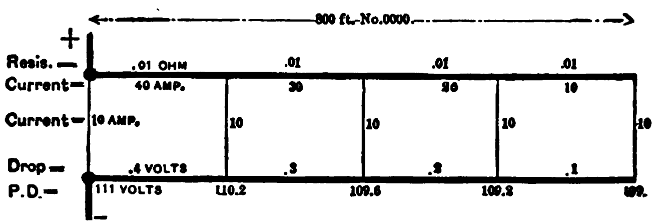


Fig. 13. Feeding at One End of Mains; 1025 lbs. Copper; 2 Volts Max. Difference Between Lamps; 111 Volts at Feeding-Points; 1.2 Volts Average Drop.

.01 ohm. The current in the first section of the + main is 40 amperes, since it supplies 4 groups of lamps taking 10 amperes each, hence the drop is $40 \times .01 = .4$ volt. Similarly the drops in the other three sections are found to be .3 .2 and .1 volts respectively. The drop in the – main has exactly the same values, but is in the opposite direction, the fall of potential being always in the

* U. S. Patent, No. 264,642, Sept. 19, 1882.

direction in which the current flows. The distribution of potential is shown in an exaggerated manner in Fig. 14. It will be seen that a potential of 111 volts, supplied at the feeding-points, gives 109 volts at the other end, therefore no lamp receives a pressure more than one volt greater or less than the normal value of 110 volts.

The horizontal axis *OO* would represent the line of zero potential when the system is uniformly insulated, in which case the potentials of the mains at the feeding-points would be + 55.5 volts and – 55.5 volts respectively. A defect in the insulation at any point would tend to cause the potential of that point to approach zero, as already explained in connection with Figs. 4 and 5; and if the – feeding-point were grounded, the + feeding-point would

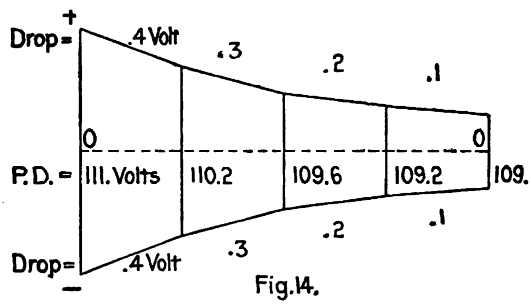


Fig. 14. Potential Diagram Corresponding to Fig. 13.

become + 111 volts, all the potentials having positive values. But the potential *difference* would remain the same in all cases.

Tapering Conductors. — The use of tapering or "conical" conductors in place of the ordinary cylindrical ones is hardly practicable, on account of the difficulty of making a wire or rod of that form. It is possible, however, to use a jointed conductor composed of sections of different sizes of wire. The object of such an arrangement is to proportion the cross-section of the conductor to the current which it has to carry in cases where the current varies from point to point, this being the usual condition in parallel distribution. If Fig. 13 be modified in such a way that the size of each section of the main is proportional to the current passing through it, Fig. 15 is obtained. In this case the drop in each section will be .25 volts, being the same for all. Hence the potential falls uniformly from the + feeding-point to the end of the

main, and would be represented by a straight line, instead of the broken one in Fig. 14.

It is sometimes stated that the use of tapering mains secures economy in copper, but such is not the case in ordinary parallel distribution. The weight of copper required in Fig. 15 is 1,013 lbs., which is practically the same as the 1,025 lbs. called for in Fig. 13. The fallacy arises from the fact that the conductor is assumed to be a true cone, the elements of which are straight lines. As a matter of fact, the elements would curve outward since the cone should be one-half the cross-section, or $\frac{1}{\sqrt{2}} = .707$ of the diameter at a point midway between the base and the apex, instead of one-half the diameter.

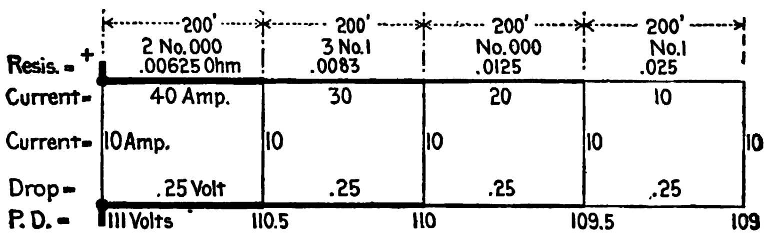


Fig. 15, Tapering Mains; 1,013 lbs. of Copper; 2 Volts Max. Difference Between Lamps; 111 Volts at Feeding-Points; 1 Volt Average Drop.

Tapering conductors give a uniform drop, as already stated; and the *average* drop is slightly less than with cylindrical wires, being 1.2 volt in Fig. 13, and 1 volt in Fig. 15. This is not a matter of great consequence, however, as it is customary to consider the *maximum* drop in electrical distribution, and that is the same for the two cases when all the lamps are connected. If only the first groups of lamps were lighted, the tapering conductors would give considerably less drop than cylindrical ones. Nevertheless, it is doubtful in practice if the advantages are worth the extra trouble of laying and connecting several different sizes of wire. Where the distances are considerable, and where joints or cut-outs would be introduced in any event, it may be desirable to vary the size of a main in proportion to the current it is to carry at different points. In this discussion it is of course assumed that the conductor must always have sufficient current capacity, whether it be tapering or cylindrical.

In the next case, Fig. 16, the mains are supposed to be fed at their centers, as shown. In this arrangement No. 2 wire, weighing 321.5 lbs., gives almost exactly the same variations of potential as in the two preceding cases, the maximum pressure being 111

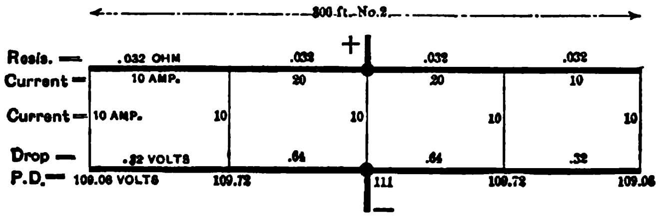


Fig. 16. Feeding at Middle of Mains; 321.5 lbs. Copper; 1.92 Volts Max. Difference Between Lamps; 111 Volts at Feeding-Points; 1.3 Volts Average Drop.

volts and the minimum 109.08 volts. This shows that a great saving of copper is effected by simply feeding the mains in the middle rather than at the ends. Theoretically, it would only require one-quarter as much copper in the former case. This is easily seen, when it is considered that the mains in Fig. 16, on each side of the feeding-point, are one-half as long, and carry about one-half as much current, as those in Fig. 13, consequently the conductor need only have one-quarter of the cross-section to give the same drop. The weight is found to be slightly more than one-quarter in the example, because the average current is in the proportion of 15 to 25 instead of 1 to 2.

The next case, Fig. 17, represents the mains fed at opposite points. This was formerly called the *Werdermann* system, after

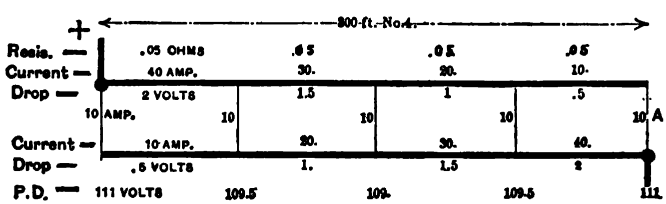


Fig. 17. Feeding at Opposite Ends of Mains; 202.2 lbs. Copper; 2 Volts Max. Difference Between Lamps; 116 Volts Between Feeding-Points; 6 Volts Average Drop.

its inventor, but is now known as the *anti-parallel* or *return loop* method of distribution. In this case the same length (1,600 feet) of No. 4 wire, weighing only 202.2 lbs., gives an equally good distribution of potential. It is sometimes supposed that this ar-

rangement must give a perfectly uniform pressure at the lamps, since the sum of the distances of each lamp from the feeding-points measured on the two mains is a constant. As a matter of fact, however, the middle lamps will receive a lower voltage than those at the ends, as shown in the diagram. This is due to the fact that the former are supplied through the portions of the main conductors which carry heavy currents, and in which the drop is greatest. For example, the drop on the mains in the case of the central group of lamps is

$$2 + 1.5 + 1.5 + 2 = 7 \text{ volts},$$

but for the end group of lamps it is only

$$2 + 1.5 + 1 + 0.5 = 5 \text{ volts}.$$

It is possible, however, to secure a perfectly uniform pressure at all points between the mains, if their cross-section is made proportional to the current in each section by the use of the so-called conical conductors already described. In this way the drop in each section will be the same, and each group of lamps will receive exactly the same pressure, being equal to the difference of potential between the feeding-points minus the drop in four sections.

In the next example the mains are fed at distributed points as represented in Fig. 18. In this case No. 7 wire, weighing only

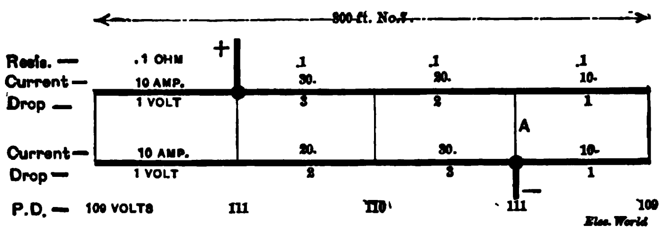


Fig. 18. Feeding at Distributed Points on Mains; 101 lbs. of Copper; 2 Volts Max. Difference Between Lamps; 116 Volts Between Feeding-Points; 6 Volts Average Drop.

101 lbs., gives no greater variation in voltage (i.e. one volt from the normal) than No. 0000 wire, weighing 1,025 lbs., in Fig. 13. These examples show the great difference that is made by changing the points at which the feeders are connected to the mains.

It should be carefully noted, however, that in both the last two cases (Figs. 17 and 18) the feeders must supply 116 volts to the mains instead of only 111 volts, as in the preceding examples

(Figs. 13, 15, and 16). In Fig. 17, for instance, the difference of potential between the feeding-points + and – must be 116 volts, in order that the end group of lamps *A* shall receive 111 volts, since there is a drop of

$$2 + 1.5 + 1 + 0.5 = 5 \text{ volts.}$$

in the upper main. Similar reasoning applies to the group *A* in Fig. 18, the drop being $3 + 2 = 5$ volts. This necessity for supplying a considerably higher voltage at the feeding-points of the mains is disadvantageous in two respects. First, it involves a loss of power in watts equal to the extra pressure multiplied by the total current; and second, it may allow great variations in poten-

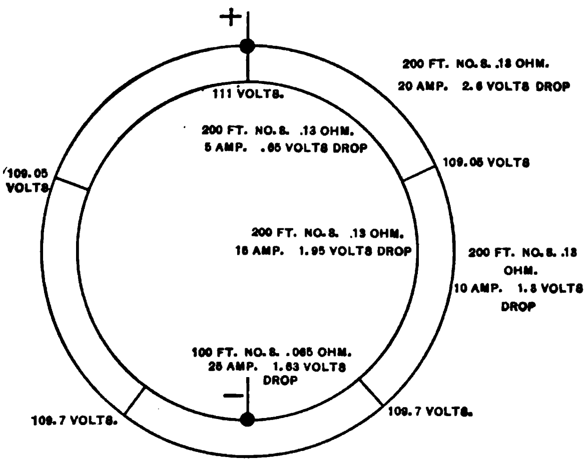


Fig. 19. Closed Ring; 2,000 ft. No. 8; 100 lbs. Copper; 115.23 Volts Between Feeding-Points; 1.95 Volts Max. Difference Between Lamps; 5.53 Volts Average Drop.

tial to occur when a large number of lamps are thrown on or off the circuit. For example, if all the lamps except one were put out, the remaining one would receive practically the full pressure of 116 volts. This may be overcome by reducing the voltage of the feeders when lamps are disconnected, either by automatic or hand regulation, employing some of the methods described later; but it is evidently simpler to maintain the same pressure at the feeding-points. On the other hand, the drop in the feeders themselves must be overcome by raising the voltage at the generating plant when the current carried by them increases. In such cases it may not involve very much additional trouble to regulate for the drop in the mains as well as for that in the feeders.

A further extension of the principles shown in Figs. 17 and 18 is indicated in Fig. 19, in which five groups of lamps are connected across the mains, which form complete circles, being fed at diametrically opposite points. In this case, 2,000 feet of No. 8 wire, weighing 100 lbs., is used, instead of 1,600 feet, as in the previous examples. A similar arrangement is shown in Fig. 20; but the lamps are assumed to be divided into four groups, of 25 lamps each. All the lamps receive exactly the same voltage, 1,600 feet of No. 10 wire, weighing only 50 lbs., being required. This exact equality in voltage is due to this being a special case, in which the lamps happen to be symmetrically placed with respect to the feeding-points. In Fig. 17, for example, the second and fourth groups

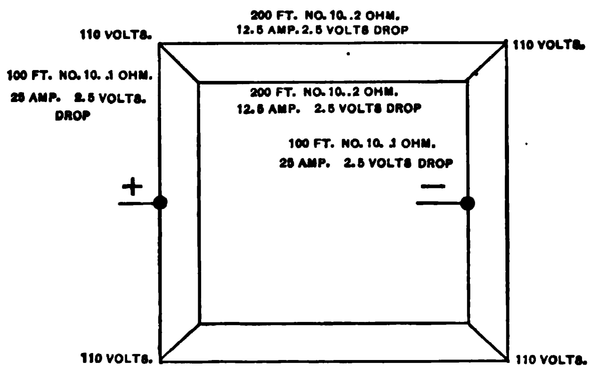


Fig. 20. Closed Square; 1,600 ft. No. 10; 50.3 lbs. Copper; No Difference Between Lamps; 117.5 Volts Between Feeding-Points; 7.5 Volts Average Drop.

of lamps have exactly the same voltage, since they are equally distant from the feeders. The pressure at the feeding-points is 117.5 volts in Fig. 20, being higher than in any of the other cases.

Individual Conductors. — The most certain way to obtain a constant voltage in parallel distribution is to provide each lamp or group of lamps with its own particular conductors. One arrangement of this kind is illustrated in Fig. 21, five groups of lamps, each taking 10 amperes and placed 200 feet apart, being assumed, as in the previous examples. The feeding-points, marked + and —, are supposed to be located at some distance from the lamps, as shown. The pair of conductors that supply each group are so proportioned in size and length that the drop has an equal value for all of the groups. This condition will be secured if the cross-

sections of the various conductors are respectively proportional to their lengths. For example, a conductor twice as long as another should have double the cross-section, so that the resistance of the two will be equal. If the currents are not the same for the different conductors, the cross-sections should be further modified in proportion to the currents. In other words, for all of the pairs of conductors, the fraction $\frac{il}{a}$ should have the same value, i being the current in amperes, l the total length of both conductors, and a the cross-section.

It is not apparent what advantages this plan of using individual wires has over the arrangements already described, the weight of copper being even greater than that in Fig. 18, for example. The

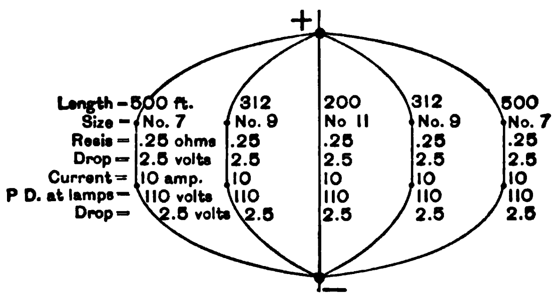


Fig. 21. Individual Conductors; Unequal Lengths; 186 lbs. Copper; No Difference of Voltage Between Lamps; 115 Volts Between Feeding-Points; 5 Volts Drop.

answer is to be found in the fact that the groups of lamps in Fig. 21 are not only equal in potential when all are burning, but they are also independent of one another, the turning on or off of one or more groups not affecting the others, provided that the voltage at the feeding-points + and – be kept constant. In the preceding cases, the throwing off of some lamps would vary the pressure of all the others. In fact, it was pointed out that disconnecting every lamp but one would raise its potential practically the whole amount of the drop, which was five or six volts in some instances. It was also stated that the remedy for this variation consists in regulating the pressure at the feeding-points. Thus it appears that it is necessary to maintain a constant voltage at the feeding-points, with some arrangements of conductors, and a variable voltage with others. These questions will be considered later under feeder regulation.

Fig. 22 represents another example of individual conductors, but in this case each group of lamps is supplied through the same total length of conductor; i.e., 800 feet of No. 8 wire, having 0.5 ohm resistance. Consequently the drop is five volts for all, since each group takes 10 amperes. The advantage of this plan over that shown in Fig. 17, which it somewhat resembles, is the freedom from interference already explained. It should be noted, however, that in either Fig. 21 or 22 the turning off of a portion of the lamps in one particular cluster would affect the remaining ones in that group. In order to secure complete independence of operation for every lamp in a system, it would be necessary to provide each one with its own individual wires. This is practically out of the question in almost all cases; but it can be approximated more or less closely, the tendency in the best practice being to subdivide the circuits and reduce the number of lamps on each, as far as economy and simplicity will reasonably allow.

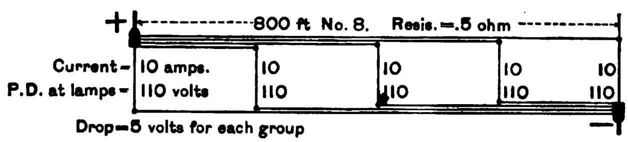


Fig. 22. Individual Conductors; Equal Total Lengths; 200 lbs. Copper; No Difference of Voltage Between Lamps; 115 Volts Between Feeding-Points; 5 Volts Drop.

Calculations of Drop, Weight, etc., of Mains. — The examples already given (Figs. 13 to 22) show the results obtained by different arrangements of mains and feeding-points in parallel distribution. These cases having been treated concretely with definite sizes of wire, voltages, currents, etc., bring out the facts clearly, and are intelligible to those who may not possess special mathematical knowledge. It will be well, however, to discuss these important problems in a more general way before dismissing them. For this purpose the following symbols may be adopted: —

L is the length of each main in any desired units;
l, the length of each section of main (i.e. between adjacent lamps);
I_0 and $-I_0$, the currents in the two mains at the feeding-points;
i and $-i'$, the currents in the two mains at the point x;
V_0 and v_0, the potentials on the two mains at the feeding-points;
u_0, the potential difference between the two feeding-points, or between one feeding-point and the opposite point on the other main;

$V' - v' = u'$, the potential difference between the two mains at any point distant x units from + feeding-point;
D, the fall of potential or "drop" at any given lamp with respect to the difference of potential between the two feeding-points;
C, the current consumed by each lamp;
N, the number of lamps;
R, the resistance of each main per unit of length.

Considering first the ordinary parallel circuit represented in Fig. 13, the drop on both mains from the first to the second lamp (or group of lamps) is $2\,R\,l\,C\,(N-1)$, and the total drop from the feeding-points to the last lamp

$$D = 2\,R\,l\,C\,[(N-1) + (N-2) + \cdots 1].$$

In this equation there are $N-1$ terms, having an average value of $\frac{N}{2}$; hence we have —

$$D = R\,l\,C\,(N^2 - N), \tag{1}$$

and the resistance per unit of length which will give this maximum drop D, is —

$$R_1 = \frac{D}{l\,C\,(N^2 - N)}. \tag{2}$$

In the case illustrated in Fig. 16 the current divides, one-half flowing in each direction, so that it is only necessary to substitute $\frac{N}{2}$ for N in the above formulæ, or

$$D = \frac{R\,l\,C}{4}\,(N^2 - 2\,N) \tag{3}$$

and

$$R_2 = \frac{4\,D}{l\,C\,(N^2 - 2N)}. \tag{4}$$

In the case of anti-parallel distribution (Fig. 17) the drop to any lamp, say the xth from the + feeding-point, is $R\,l\,C\,[(N-1) + (N-2) + \cdots x]$ on the + main, and $R\,l\,C\,[(N-1) + (N-2) + \cdots (N-x+1)]$ on the − main. Hence the total drop on both mains is the sum of these values which is —

$$D = \frac{R\,l\,C}{2}\,(N^2 + 2\,Nx - 3\,N + 2\,x - 2\,x^2). \tag{5}$$

From this equation it is evident that the drop depends upon x. Differentiating (5), we find that D is a maximum when

$$x = \frac{N+1}{2},$$

that is, in the middle of the circuit. In fact, this is evident without calculation, for the reasons given on page 34. Substituting this value in (5), we find that

$$D_{max} = \frac{RlC}{4}(3N^2 - 4N + 1). \tag{6}$$

The drop is a minimum when $x = N$ or 1, that is, at either end of the circuit. Hence substituting in (5), we have —

$$D_{min} = \frac{RlC}{2}(N^2 - N). \tag{7}$$

This last equation might have been obtained directly from (1); for evidently in the anti-parallel system (Fig. 17), the drop at the first or last lamp is one-half the drop at the last lamp in the ordinary parallel circuit (Fig. 13), provided the mains are of the same size.

By subtracting (7) from (6) we obtain the greatest difference in pressure between any two lamps in the circuit —

$$D_{max} - D_{min} = \frac{RlC}{4}(N^2 - 2N + 1), \tag{8}$$

and
$$R_3 = \frac{4(D_{max} - D_{min})}{lC(N^2 - 2N + 1)}. \tag{9}$$

The relative economy of the three systems can now be found. The weights of copper required are inversely proportional to the resistances; hence calling A_1, A_2, and A_3 respectively the cross-sections (in circular mils, for example) of the mains, which will produce the same maximum difference in pressure between any two lamps, we have from (2), (4), and (9) —

$$\begin{aligned} A_1 : A_2 : A_3 &= \frac{1}{R_1} : \frac{1}{R_2} : \frac{1}{R_3} \\ &= 4(N^2 - N) : (N_2 - 2N) : (N^2 - 2N + 1). \end{aligned}$$

Hence the simple parallel system (Fig. 13) requires more than four times as much copper as when the mains are fed in the middle (Fig. 16), but there is very little difference between the latter and the anti-parallel method (Fig. 17). This comparison is made on the basis of a certain maximum *difference* in pressure between any two lamps on the circuit. If we consider the same *total drop*, the advantage of the plan illustrated in Fig. 16 is much greater. The

relative weights of copper required by the three systems then become from (2), (4), and (6) —

$$A_1 : A_2 : A_3 = 4\,(N^2 - N) : (N^2 - 2\,N) : (3\,N^2 - 4\,N + 1).$$

As an example to illustrate the use of the above formulæ, let us assume that twenty 16-candle-power lamps, each taking one-half an ampere, are placed ten feet apart on mains each 200 feet long, the maximum allowable difference between any two lamps being one volt. Hence $l = 10$, $N = 20$, $C = .5$, and $D = 1$. The resistance per foot by the ordinary parallel arrangement would be from (2) —

$$R_1 = \frac{1}{10 \times .5\,(400 - 20)} = .00053 \text{ ohm},$$

which corresponds to a No. 7 wire (A. W. G.).

By the second method (Fig. 16) it would be —

$$R_2 = \frac{4}{10 \times .5\,(400 - 40)} = .00222 \text{ ohm},$$

corresponding to No. 13 wire. And by the anti-parallel system —

$$R_3 = \frac{4}{10 \times .5\,(400 - 40 + 1)} = .00221 \text{ ohm},$$

which also corresponds to No. 13 wire.

By the first two systems, however, the total drop would be but one volt, while with the anti-parallel plan, the *difference* between the lamps having the highest and lowest pressure would be one volt. This is proved by finding the drop to the first lamp, from

(7) — $$D_{min} = \frac{10 \times .00221 \times .5}{2}\,(400 - 20) = 2.09 \text{ volts},$$

and the drop to the middle of the circuit, from (6) —

$$D_{max} = \frac{10 \times .00221 \times .5}{4}\,(1200 - 80 + 1) = 3.09 \text{ volts}.$$

Hence the greatest difference in pressure is one volt, but the *total* drop to the middle lamp is 3.09 volts for the anti-parallel system. The same size of wire (No. 13) gives a total drop of only one volt, if arranged according to Fig. 16 ; and for the simple parallel method (Fig. 13), the maximum drop with No. 13 wire is found by (1) to be —

$$D = 10 \times .00221 \times .5\,(400 - 20) = 4.18 \text{ volts}.$$

In short, for the same maximum difference in voltage in the three systems, the relative weights of copper are, roughly, 4 : 1 : 1, and the total drop, 1 : 1 : 3.09 volts; while for the same weights of copper, the maximum differences in pressure are 4.18 : 1 : 1 volts, and the total drop, 4.18 : 1 : 3.09 volts.

The problems of calculating and comparing the results obtained by different arrangements of conductors in parallel distribution being of great importance in electrical engineering, it will be well to give other general methods of solving them. These are largely derived from Abbott's work on Electric Transmission of Energy, with certain modifications and corrections. Let it be supposed that the mains supply an indefinite number of lamps or other devices uniformly distributed along their entire length. This is equivalent to assuming that the current supplied by the generating plant flows between the two mains in a uniform sheet throughout their entire length.

CASE I. **Cylindrical Conductors. Parallel System.** — Fig. 23 represents two parallel cylindrical conductors connected to the source of supply at A and C. From each element, dx, of the + main AB, along its entire length, an elementary amount of current will pass to the other main, CD. Hence the current decreases uniformly from its maximum value I_0, at the point A, to 0 at the point B. At any point x, the current in the mains will be the total current I_0, minus all the current which has flowed across from one conductor to the other, between the point A and the point x under consideration. This latter quantity will be $I_0 x / L$, since the flow of current per unit of length is I_0 / L.

By Ohm's law the variation in potential in any conductor is $E = RI$. The resistance of the element dx for both mains is $2\,Rdx$; hence the drop in pressure for the element dx is given by the expression: —

$$d(u_0 - u') = 2\,R\,dx\left(I_0 - \frac{I_0 x}{L}\right) = 2\,R\,I_0\left(1 - \frac{x}{L}\right)dx. \qquad (10)$$

Integrating between $x = 0$ and $x = L$ —

$$u_0 - u' = 2\,R\,I_0\int_0^L\left(1 - \frac{x}{L}\right)dx = \frac{R\,I_0 x}{L}(2\,L - x). \qquad (11)$$

This equation, which gives the drop on both mains between the feeding-points A and C and any point x, represents a branch

of a parabola, to which the conductor may be considered as an asymptote. When $x = 0$, $u_0 - u' = 0$, showing no drop at AC which is evident; when $x = L$, $u_0 - u' = RI_0L$, being obviously the *maximum* value of the drop, its *average* value being $\frac{2}{3}RI_0L$. As an example, let it be assumed that —

$I_o = 12$ amperes. $\qquad V_o - v_o = 40.$

$L = 60$ feet.

$R = .02$ ohm per foot.

$$u_o - u' = \frac{.02 \times 12\,x}{60}(120 - x).$$

If x be successively taken as 10, 20, 30, 40, 50, and 60, the corresponding values for the drop are 4.4, 8.0, 10.8, 12.8, 14.0, and 14.4 volts, from which the curve EF in Fig. 23 is plotted. The curves in Figs. 24, 25, and 26 are also plotted from the same

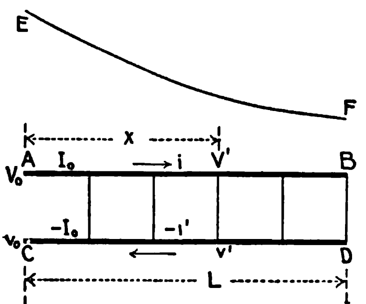


Fig. 23.

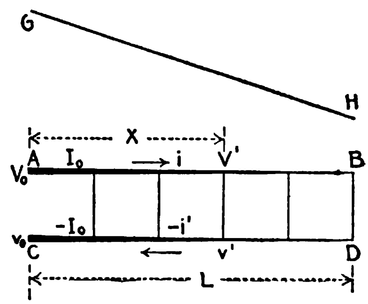


Fig. 24.

Figs. 23 and 24. Parallel Distribution. Cases I. and II.

data. An inspection of this curve indicates an unequal drop along the conductors, evidently due to varying current density in the mains. To avoid this variation it is possible to employ tapering, or so-called "conical," conductors, already referred to on page 31.

CASE II. **Tapering Conductors. Parallel System.** — In Fig. 24, AB and CD are two parallel tapering conductors, supplied with current at A and C, and having a cross-section which is proportional to the current at any point, so that the current density will be constant. The same notation as in Case I. will be used, except that R_0 is the resistance of each main per unit of length at A or C, the resistance per unit of length at any other point, x, being represented by r, which is evidently a variable. The drop or variation in potential for any element now becomes —

$$d(u_o - u') = 2\,r\,dx\left(I_o - \frac{I_o x}{L}\right). \qquad (12)$$

But $r = \rho / S$ at any point, ρ being the specific resistance and S the cross-section of the conductor at that point; hence —

$$d(u_0 - u') = \frac{2\rho\,dx}{S}\left(I_0 - \frac{I_0 x}{L}\right) = \frac{2\rho I_0\left(1 - \frac{x}{L}\right)dx}{S} \qquad (13)$$

But the current density which, by hypothesis, is constant, is —

$$\frac{I_0\left(1 - \frac{x}{L}\right)}{S}.$$

Hence by integrating (13), we have —

$$u_0 - u' = 2 R_0 I_0 x. \qquad (14)$$

This is the equation of a straight line, indicating a uniform drop from AC to BD; $u_0 - u'$ being a maximum when $x = L$, and having a value $2\,R_0 I_0 L$, which is twice as great as in Case I. This demonstrates that, with a tapering conductor having the same resistance per unit of length at the supply point as a cylindrical one, there is twice the drop. It is also a fact that the weight of copper is one-half as much for the former; since it is not a true cone, the diameter at the middle section being .707 instead of half that at the base, as already explained on page 32. Such a conductor might also be considered as a *wedge*, two of the sides of which are parallel.

Consequently, with the same weight of copper, there is no reduction in the *maximum* drop when so-called conical conductors are employed, as has been claimed. There is, however, a saving in the *average* drop, which is readily seen by comparing the curves EF and GH in Figs. 23 and 24, or by substituting $\frac{1}{2}L$ for x in (11) and (14), which give $\frac{3\,RI_0 L}{4}$, as the drop at the middle point of the mains in Case I., and $\frac{RI_0 L}{2}$ in Case II. The latter value assumes that the area of the base of the tapering mains is made twice as large as for the cylindrical ones, in order that the weight of copper shall be the same for both. Hence the drop at the *middle point* is $\frac{2}{3}$ as great in Case II. as in Case I., the *maximum* drop being the same, and the *average* drop being $\frac{2}{3}$ as much. The *loss of energy* corresponds to the average drop, hence it is also $\frac{2}{3}$ as great for the tapering conductors. Usually, however, the

maximum drop is the controlling consideration in designing electrical conductors, particularly for electric lighting.

CASE III. **Cylindrical Conductors. Anti-Parallel System.** — In this case the mains are fed from opposite ends as already described in connection with Fig. 17. It is evident that this arrangement differs from the two preceding in the fact that no lamp receives the full voltage delivered to the mains, because V_0 is at one end of one main, and v_0 is at the opposite end of the other.

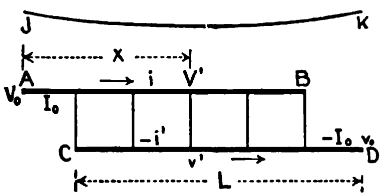


Fig. 25.

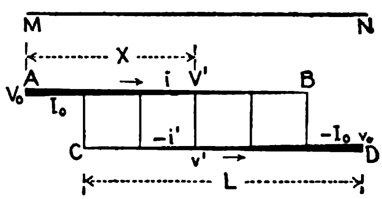


Fig. 26.

Figs. 25 and 26. Anti-Parallel Distribution. Cases III. and IV.

A study of Fig. 25 shows that the variation in pressure between the ends of any element dx for both mains is equal to the *difference* between the drop in one main and that in the other, whereas in the two previous cases it was the *sum* of the two drops, hence —

$$d\,(u_0 - u') = R\,dx\,(i - i'), \tag{15}$$

i and $-i'$ being the currents in the respective mains at the point x, and having the following values : —

$$i = I_0 - \frac{I_0}{L}x \quad \text{and} \quad -i' = \frac{-I_0}{L}x.$$

substituting these in (15), we have —

$$d\,(u_0 - u') = R\,I_0\left(1 - \frac{2\,x}{L}\right)dx. \tag{16}$$

Integrating —

$$u_0 - u_1 = R\,I_0\int_0^L\left(1 - \frac{2\,x}{L}\right)dx = \frac{R\,I_0\,x}{L}(L - x). \tag{17}$$

This equation is also that of a parabola, but its axis is perpendicular to the mains at their middle point. When $x = 0$ or $x = L$, $u_0 - u' = 0$, showing that at each end the lamps receive the same voltage. To locate the maximum difference in pressure between the lamps —

$$d\left(\frac{u_o - u'}{dx}\right) = R I_o \left(1 - \frac{2x}{L}\right) = R I_o - \frac{2 R I_o x}{L} = 0,$$

$$x = \frac{L}{2}, \tag{18}$$

that is, the greatest drop is at the center of the mains, and has the value $RI_0L / 4$ obtained by substituting (18) in (17). But it should be carefully noted that this represents the *difference* between the voltage of the middle lamp and that of either end lamp. For the latter the pressure is less than the difference of potential between the feeding-points ($= V_0 - v_0$) by the quantity $RI_0L / 2$, which is the total drop in either one of the mains. Hence the middle lamp receives a voltage which is less than that supplied to the feeding-points by an amount —

$$\frac{R I_0 L}{4} + \frac{R I_0 L}{2} = \frac{3 R I_0 L}{4}. \tag{19}$$

This value is only three-quarters as large as the maximum drop in Case I., which was found to be RI_0L; and the greatest *difference* between the voltage of lamps is only one-quarter as much, or $RI_0L / 4$, the weight of copper being the same.

CASE IV. **Tapering Conductors. Anti-Parallel System.** — The plan of feeding from the opposite ends of the mains may be applied to tapering conductors with even greater advantage than in the case of cylindrical conductors. By applying the equations in Cases II. and III. to this arrangement, shown in Fig. 26, the following expression is obtained: —

$$d(u_o - u_1) = (ri - r' i')\, dx.$$

r and r', as well as i and $-i'$, being respectively the resistances and currents in the two mains at the point x. Hence by a train of reasoning similar to that in the previous cases, $r = \rho / S$, and $r' = \rho / S'$; but $\rho i / S$ and $\rho i' / S'$ are constants for each main, by hypothesis, and are equal to each other, hence —

$$d\frac{(u_o - u')}{dx} = 0. \tag{20}$$

$u_0 - u' =$ a constant, and

$$V' - v' = V_o - v_o - R_o I_o L. \tag{21}$$

In other words, there is no *difference* in the voltage supplied to the various lamps, the pressure at any lamp being the difference

in potential between the feeding-points less the quantity R_0I_0L, which latter is therefore the maximum drop for all of the lamps. This is the same value as in Case I., but the amount of copper is only one-half as great; hence the maximum drop is one-half as much for the same weight of copper, and all lamps receive the same voltage.

Drop in Voltage with Irregular Distribution of Lamps. — In the various cases heretofore considered (Figs. 13 to 26 inclusive), the lamps were assumed to be uniformly distributed on the mains. This represents not only ideal conditions, but also applies fairly well to actual practice at full load; that is, when the maximum number of lamps are lighted. In fact, the circuits should be carefully designed to approximate this condition as closely as practicable in most cases. When only a fraction of the lamps are turned on, it is evident that they may be very irregularly distributed. This would give rise to an almost infinite number of special problems corresponding to the possible arrangements that might be made; but there are certain general facts that apply to such cases.

If in Fig. 13 it be assumed that only the last or right-hand group of lamps is connected, the drop would be equal to the current multiplied by the total resistance of both mains, or $10 \times .08 = .8$ volt. Hence the potential difference supplied to this group of lamps would be the pressure at the feeding-points minus the drop, that is, $111 - .8 = 110.2$ volts. If now the middle group of lamps be turned on also, the potential difference which they receive would be $111 - 20 \times .04 = 110.2$ volts, and the pressure at the last group becomes $111 - (20 \times .04 + 10 \times .04) = 109.8$ volts. Thus the various groups may be lighted successively, and it will be found that —

1. The addition of each group reduces the pressure for all of those already connected.
2. The maximum drop occurs when all of the lamps are connected.
3. The greatest *difference* between the voltage of any two lamps will usually exist when all are turned on.

The first statement might be contradicted on the ground that the pressure at the first group of lamps connected directly to the feeding-points would remain the same whether the others were

lighted or not. Theoretically this is true; but practically there would be some drop on the mains even for this group, unless it were connected exactly at the feeding-points; and there would always be a drop on the feeders when any lamps were turned on, unless it is overcome by some of the special methods of feeder regulation which will be described later.

The same statements apply to Fig. 16, in which the portions of the mains on each side of the feeding-points may be considered as corresponding to the whole mains in Fig. 13. Even though all the lamps on one side were connected, and only one on the other side, the total drop and the difference between the voltage of lamps would be no greater than for the full-load conditions represented in the diagram.

Similar reasoning is applicable to the arrangements shown in Figs. 17 and 18; in fact, any two groups of lamps would have the same pressure in the case of the former, and any number less than all would give no greater total or difference in drop than the full load of lamps. If the first three groups were lighted, and only a single lamp out of the last group was turned on, the latter might receive a potential about three volts higher than that of the others. This is greater than the maximum difference when the circuit is fully loaded, which is only two volts. Hence it appears that when one end of a pair of anti-parallel mains is heavily loaded, and there are very few lamps in circuit at the other end, the difference between the voltage of lamps at the two ends is greater than when the full load is turned on. Consequently this is an exception to statement 3 above. But even in this case, the maximum drop and the average drop are less with a fractional load.

In Fig. 27 the curves *AB* and *CD* represent the potentials on two cylindrical mains, which are fed according to the anti-parallel method at *A* and *D* respectively, being fully and uniformly loaded. The drop between *A* and *E* is greater than between *C* and *J*, because the average value of the current is greater for the former, as will be seen by comparing Fig. 17. Hence the pressure supplied to the middle lamps *EJ* is less than that at the end lamps *AC*, as already explained in connection with Figs. 17 and 25. If now all the lamps on the right-hand half of the mains be disconnected, there will be no drop between *E* and *F*, and the fall of potential from *H* to *D* will be constant, and will be represented by the

straight line HD. It is evident from an inspection of this diagram that $FD - EH > BD - EJ$, or in other words, there is a greater *difference* between the voltage at FD and EH when half the lamps are thrown off. Hence anti-parallel mains, when very unequally loaded, may show an exception to statement 3 (page 47) as already explained. It is also apparent, however, that the maximum as well as average drop are smaller with any load less than the full amount.

The substitution of tapering mains for cylindrical ones makes the pressure still more uniform for fractional loads, since the drop is more nearly equal for the different portions of the conductors.

When lamps are irregularly connected to a closed loop or ring arrangement of mains, the problem becomes somewhat more diffi-

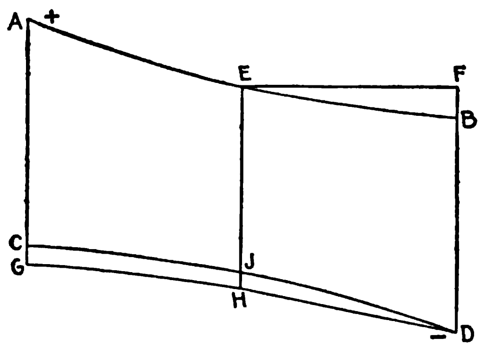


Fig. 27. Effect of Unequal Distribution of Lamps on Anti-Parallel System.

cult, since there are two paths for the current.* Such a case is represented in Fig. 28, in which a pair of ring mains are supplied at the feeding-points, with a voltage V, the total value of the current being I. The resistance of a semicircular portion of each main is R. Two equal lamps are assumed to be connected as shown, the current in each being $\frac{1}{2} I$. Let x be the current that flows downward from the + feeding-point, then the current in the upper half of mains is $I - x$, and their combined resistance is $2R$, hence, —

$$V - V_2 = 2R(I - x) \text{ or } RI - \frac{V - V_2}{2} = Rx, \tag{22}$$

and $$V - V_1 = Rx, \tag{23}$$

also $$V_1 - V_2 = R\left(x - \frac{I}{2}\right) \text{ or } V_1 - V_2 + \frac{RI}{2} = Rx. \tag{24}$$

* This matter will be discussed further under the head of "Networks" of conductors.

From (23) and (24),

$$V - V_1 = V_1 - V_2 + \frac{RI}{2}. \qquad (25)$$

From (22) and (23),

$$V - V_1 = RI - \frac{V}{2} + \frac{V_2}{2}. \qquad (26)$$

From (25),

$$V_2 = 2V_1 - V + \frac{RI}{2}. \qquad (27)$$

Substituting this value of V_2 in (26),

$$V - V_1 = RI - \frac{V}{2} + V_1 - \frac{V}{2} + \frac{RI}{4}. \qquad (28)$$

Simplifying, we have,

$$V_1 = V - \frac{5RI}{8}. \qquad (29)$$

From (27) and (29),

$$V_2 = V - \frac{3RI}{4}. \qquad (30)$$

From (23),

$$x = \frac{V - V_1}{R}. \qquad (31)$$

To take a specific case, let us assume $V = 110$ volts, $I = 8$ amperes, and $R = 1$ ohm. Then we find from (29), (30), and

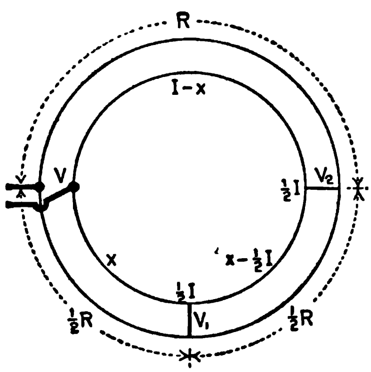


Fig. 28.

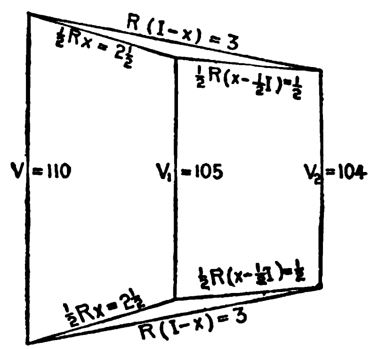


Fig. 29.

Figs. 28 and 29. Irregular Distribution of Lamps on Ring Circuit.

(31) that $V_1 = 105$ volts, $V_2 = 104$ volts, $x = 5$ amperes, the current that flows upward from the + feeding-point is $8 - 5 = 3$ amperes, the current in each lamp being 4 amperes. Fig. 29 represents the distribution of potential in this case, including the

drop in each portion of the mains. The addition of more lamps to this circuit, whether symmetrically or unsymmetrically placed, would increase the total and average drop, also the maximum difference in voltage between lamps.

The general conclusion is, that the three statements made on page 47 apply not only to the simple arrangement shown in Fig. 13, but also to almost any parallel system of mains, with the exception of peculiar conditions on an anti-parallel circuit, as explained in connection with Fig. 27. Hence it is ordinarily sufficient in practice to calculate the distribution of potential on a parallel system for full load, since the total or average drop, and the greatest difference in voltage between lamps, will almost always be smaller for any number or arrangement of lamps less than the maximum load. Heretofore the principal point that has been considered in discussing parallel systems has been the difference between the pressures supplied to the various lamps which are burning at the *same time*. But it has already been explained on page 35 that in cases where the total drop is considerable, — 10 per cent, for example, — the voltage at the lamps will rise nearly that same percentage when the full load is thrown off, leaving only a few lamps. It will now be well to study the means employed to prevent variations in the voltage of a given lamp when others are thrown on or off the same circuit.

Regulation of Voltage Supplied to Parallel Systems. — The feeding-points in the various diagrams (Figs. 13 to 29) might in some cases be supplied with current directly from the generator, or the feeders may be so short that their resistance is insignificant. Under those circumstances it would only be necessary for the dynamo or other source to generate a constant pressure in order to supply the mains represented in Figs. 13, 15, and 16. If this were kept at 111 volts, the last group of lamps would receive 109 volts at full load, and no lamp could receive more than 111 volts, even if all but one were turned out, so that the extreme variation would be but one volt from the normal pressure of 110 volts. The large amount of copper used in these cases saves the trouble of regulation, and often might be worth the extra first cost.

This is practically the way that the majority of isolated plants are operated, the size of the wires being made sufficient to limit the drop to a small amount so that the dynamos may be run at a

fixed voltage. With wiring designed for a total drop of 4 per cent, the greatest variation from the average pressure would only be about 2 volts, and usually the maximum drop is between 2 and 4 per cent for isolated plants where the distances are moderate. In most cases, even the simplest, feeders are employed to connect the mains with the generators, so that the pressure lost in them must be included in determining the total drop. When the distances are greater, or it is attempted to save copper by using smaller conductors or by adopting such arrangements of mains as those represented in Figs. 17 to 22, the drop becomes too large to warrant the maintaining of a constant potential at the dynamo. Nevertheless, many small central stations and isolated generating plants are operated at an approximately fixed voltage, in spite of the fact that the drop may be 5 per cent or more. The usual practice in such cases is to run the dynamos about 2 per cent above the normal voltage of the lamps, the consequence being that at full load the latter receive about 3 per cent less pressure than that for which they are intended, assuming the drop to be 5 per cent. This custom arises from the fear of shortening the life of incandescent lamps by feeding them with too high a voltage.

It appears to be a generally accepted idea that the rated pressure of a lamp is a *limit* above which it should never be allowed to rise. As a matter of fact, the voltage marked on the lamp should be considered as an *average* value, to be approximated as closely as possible at all times. It is a rare thing to see incandescent lamps burning even one or two per cent above their rated pressure, while they are very often operated considerably below this point. The author has observed in thousands of cases in America and Europe that incandescent lamps are usually run perceptibly below their proper voltage, and at least half of them are so low that they are positively dim. This is partly due to the usual falling off in the candle-power of lamps which occurs after they have burned for some time, amounting to a considerable loss after a run of 500 hours. This matter will be treated fully under the head of incandescent lamps. In isolated plants, and in many central stations where lamp renewals are paid for by the user, this diminution in candle-power is great because of the tendency to unduly prolong the life of the lamps. But in stations or plants where it is desired to render good service, the lamps are renewed more frequently.

The reason for generating a constant potential is the simplicity and convenience secured by so doing. The attendant merely has to keep the index of the volt meter at a certain point, by means of the ordinary rheostat in the shunt field circuit, being either instructed to do so, or naturally falling into that habit. It would greatly improve the service, however, if the pressure were kept at a given value for any number of amperes up to half load, and raised a certain percentage when the current exceeds that amount. For example, below half load the dynamo could be regulated to generate 2 volts higher potential than the normal voltage of lamps, which would again be increased 2 volts when the current is greater than half load, the total drop being 5 volts. In this way the pressure at the lamps would not be more than one or two volts high or low at any time, and the extra trouble or intelligence required would certainly be insignificant. Indeed, it would seem to be perfectly practicable to carry this plan further, and subdivide the load into three or even four parts instead of two. The instructions could be just as definite and almost as easily carried out as for one fixed potential. If this regulation were effected by hand, using the ordinary rheostat in the field circuit, it would be a rough approximation to the rise in voltage with increasing load which occurs automatically in an "over-compound" dynamo

Regulation by Means of Compound or Over-Compound Dynamos. — It would seem that an excellent way to operate systems in which a constant potential is required at the lamps or other receivers, is to employ generators which are over-compound wound to give a rise in voltage from no load to full load the same in amount as the total drop, thus automatically securing the desired result. An objection to this plan is the tendency for the *E.M.F.* of the dynamo to rise, and a very excessive current to flow in case of a short-circuit. The *E.M.F.* of a plain shunt machine, on the other hand, tends to fall with a short-circuit. But when properly protected by fuses or circuit-breakers this difficulty is not likely to be serious. Another difficulty that may arise in such a case is the fact that when there are two or more over-compound generators the pressure may be too high when only one is in use. For example, when one machine out of two is running with one-half of the total load, it will raise the voltage just as much as if both were working at full load, whereas it should only increase the pressure

one-half of the maximum percentage of drop. This trouble may be avoided by always leaving in circuit the series coils of all the dynamos, or preferably by substituting an equivalent resistance for them when they are disconnected.*

The manner of connecting two or more compound dynamos to operate in parallel is represented in Fig. 30. *A* is the armature, *B* the series, and *C* the shunt field coils, *R* the field rheostat, *D*, *F*, are switches connecting the main terminals of the dynamo with the 'bus bars *G* and *I* respectively, and *E* is a switch to connect

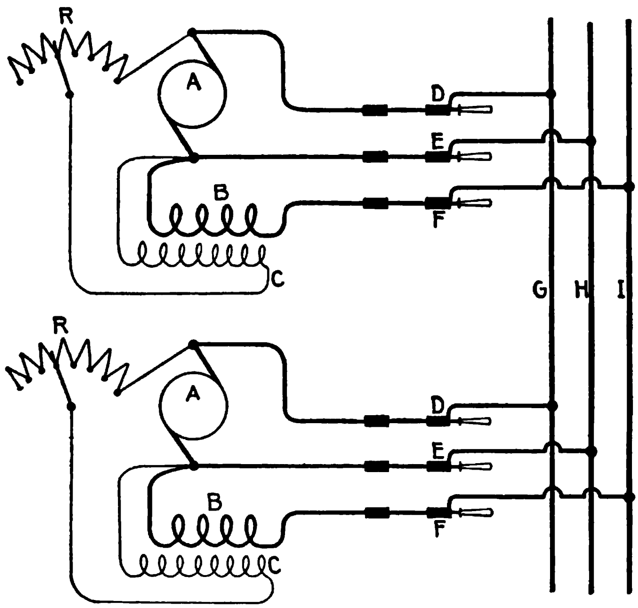


Fig. 30. Compound Dynamos in Parallel.

the equalizer † *H* with the brush from which the series coil *B* leads. It is a common practice to mechanically join *D*, *E*, and *F* by a cross-bar so that they move together and form a three-pole switch. In such cases, when a dynamo is about to be connected to the circuit, the switches *D*, *E*, and *F* are left open, and the field magnet is excited by the shunt coil *C*, being regulated by the rheostat *R* until the pressure generated is a little greater (about one per cent) than the difference of potential between the 'bus bars *G* and *I*. This fact may be ascertained by comparing two volt meters

* This matter is explained in vol. i., p. 349. † Vol. i., p. 348.

respectively connected to the dynamo and to the 'bus bars, or by connecting a single volt meter first to one and then to the other, which avoids the error due to a difference between two instruments. A still better plan is to connect the dynamo to the 'bus bars through a high resistance and a galvanometer which deflects one way or the other according to whether the dynamo voltage is higher or lower than that of the circuit. For this purpose it is very convenient to use a volt meter having a scale on both sides of the zero point. After the pressure of the dynamo has been properly regulated, the three switches, *D*, *E*, and *F*, are closed. When this is done simultaneously with a three-pole switch, a considerable current will flow through the series coil *B*, which tends to still further increase the voltage of this dynamo, at the same time taking current away from the series coils of the other machines, and thereby reducing their potential. The shifting of load thus produced may be so sudden and so great as to be objectionable. To avoid this difficulty the two switches *E* and *F* are sometimes combined to form a double-pole switch, the other one, *D*, being operated independently. With this arrangement the double-pole switch *EF* is closed first, allowing the current to flow through the series coil *B*, and the regulation of voltage is made under these conditions. The switch *D* is then closed, and the *E.M.F.* of that machine will not change materially. The current which it generates will also be small, provided its voltage was adjusted to be only slightly greater than that of the 'bus bars.

When the three switches, *D*, *E*, *F*, are simultaneously closed, it is found in practice that armature reaction, etc., tend to lower the potential of the generator about as much as the current in the series coil tends to raise it, hence the effects counteract each other. But it is merely an accident if such is the case, and it can only be determined by trial. It often happens that the two actions do not balance each other, the rise of *E.M.F.* being greater than the fall. In these cases, which are common in electric railway stations, the attendants learn by experience that the pressure of a dynamo should be regulated a certain number of volts below that of the 'bus bars before it is connected to them, in order that it shall act properly when the three-pole switch is closed. This is certainly a crude method of working, and increases the chance of having a back current flow through the series coil, which would tend to

demagnetize the field if the *E.M.F.* of the dynamo is considerably less than the pressure at the 'bus bars, particularly when the equalizer is somewhat long or is too small in cross section.

It would seem to be generally desirable to separate the switch *D* in order to have independent control of the equalizer. Another advantage secured by this arrangement is the field excitation that is positively produced when the switch *E F* is closed, avoiding the delay and uncertainty which are always involved when self-excitation alone is depended upon. In fact, self-exciting dynamos often fail to generate, or become reversed in polarity.* The use of separate switches also enables the series coil to be left in circuit when a dynamo is not working, for the reasons explained on page 53. The three switches *D*, *E*, and *F* might all be made independent; but there would then be a chance for *D* and *F* to be closed, and the equalizer switch *E* left open, which is likely to cause serious trouble, due to an excessive or reversed current in the series coil *B*; or the switches *D* and *E* might happen to be closed with *F* open, in which event the series coil would not be in circuit, and the dynamo could not generate sufficient voltage when the load increased.

Compound or over-compound generators are generally used in isolated plants and smaller central stations, and are almost universally employed in electric railway power-houses; but in large electric-lighting stations plain shunt dynamos are often employed in order to give greater flexibility of regulation. In such systems the lamps and other devices are supplied through a number of feeders, which are fed with different pressures at the station according to their length and the load upon them. The methods employed will be described later under the head of "Feeder Regulation." It should also be noted in this connection that the business of large stations warrants the constant employment of one or more men to regulate the voltage, while in small plants the regulation should be automatic as far as possible, in order to reduce the required attendance to a mimimum. It is not unusual for such plants to be left to take care of themselves for considerable periods of time. In most cases automatic regulation has to be supplemented more or less by hand adjustment of the field rheostat to make up for change in speed due to variations in

* Vol. i., p. 362.

steam pressure or water pressure in the case of hydraulic power. The heating of the field coils and resistances in shunt and compound dynamos, as well as hysteresis in the magnets, also cause variations in the voltage which usually have to be overcome by hand regulation.

Automatic Constant-Potential Regulators. — To entirely avoid the necessity for hand regulation, or to reduce it to a minimum,

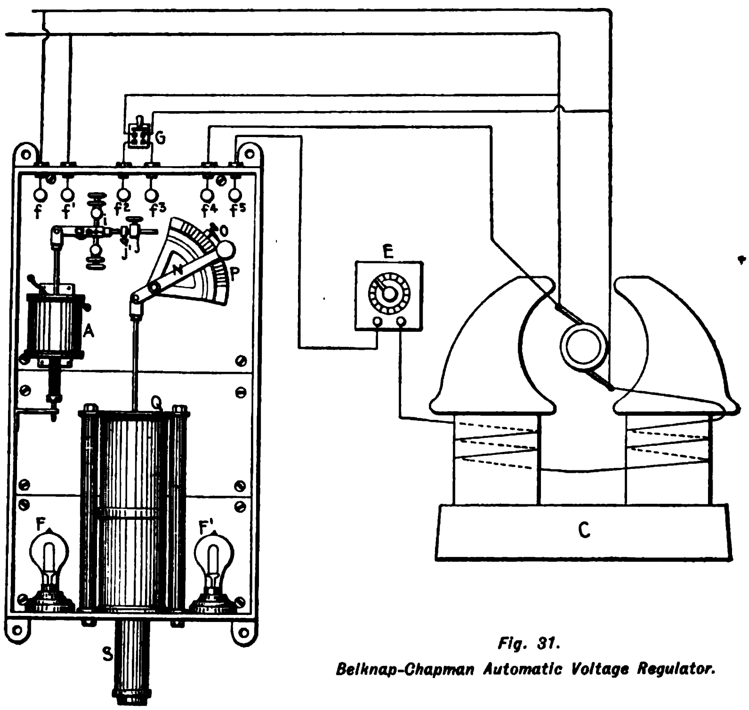


Fig. 31.
Belknap-Chapman Automatic Voltage Regulator.

automatic devices may be used to maintain constant potential. One of these regulators, illustrated in Fig. 31,* consists essentially of a rheostat in the shunt field circuit, whose moving arm, N, is operated by a solenoid, Q. A relay solenoid, A, is connected across the main conductors through the binding-posts $f\ f'$, and has contact points, i, that govern the admission of current to the working solenoid Q. The latter is differentially wound with four coils, two of which have a small continuous current flowing through them, and are in opposition to each other, the current being sup-

* *Electrical World*, N.Y., March 20, 1897, p. 395.

plied through the switch *G*, and binding-posts f^2f^3. The other two coils, when the circuit through them is closed by the relay, act to neutralize one of the continuously excited coils. This method of operation avoids the injurious sparking that would occur if the circuit of the main solenoid were actually broken, and thus permits a close adjustment of the relay contact points, and secures a more sensitive regulation. The cores of the solenoid are composed of small, soft iron wires to give quick action and reduce hysteresis effects. Two lamps, $F\ F'$, constitute a non-inductive resistance for the relay circuit. An ordinary hand rheostat, *E*, is included in the shunt field circuit in order to adjust the resistance, and also give independent control. The voltage for which the device is set may be altered by shifting the small weight *J* on the relay lever. In this device the consumption of energy is not large, being only 60 or 70 watts for a large regulator. The construction as described would tend to maintain a constant potential at the points on the circuit to which the binding-posts $f\,f'$ are connected. It is evident that these may be in the station or at any desired position on the system of conductors, thus producing the effect of over-compound winding. This would necessitate the running of special pressure wires to some distance, which may be avoided by providing the relay solenoid, *A*, with a series coil in addition to the shunt coil, or, in short, by compounding the regulator instead of the field magnets themselves. The series coil would have to be connected in the main circuit, or shunted around a resistance placed in it.

In order to maintain a constant current for charging storage batteries and for other purposes, the relay *A* is wound with a series coil only. These devices are also made for alternating current regulation. A later form of the Chapman regulator is described in the *Electrical World*, April 16, 1898, p. 480.

Methods of Exciting the Shunt Coils of Dynamos. — The three principal ways of exciting the shunt field coils of either a plain shunt or compound generator are known as *Self excitation*, *'Bus excitation*, and *Separate excitation*.

If self-excited, the terminals of the shunt field coils are connected to the brushes, hence the magnetism gradually dies away as the dynamo is slowed down after being disconnected from the circuit; and when it stops the field has disappeared, except a little residual magnetism. This avoids the danger of piercing the insulation of

the field or armature winding, which is likely to occur if the magnetism be suddenly discharged. The disadvantages of this method are the slowness with which the dynamo builds up its own field, and the possibility that it may entirely fail to generate, or become reversed in polarity. In 'bus excitation the shunt field coils are fed from the station mains or 'bus bars, the advantages being the fact that the field magnetism is promptly and positively brought to full strength so that the dynamo may be connected to the others as soon as it attains its speed, and the polarity cannot become reversed. On the other hand, the field may be accidentally left in circuit after the dynamo is stopped, and it is always necessary to discharge it through a bank of lamps or other resistance by means of a field break switch. This method of discharge, although safe, might cause trouble if the bank of lamps were disconnected, or otherwise out of order.

With separate excitation the field circuits of the generators are connected to a special dynamo or other source of current. This plan has all the advantages and disadvantages of 'bus excitation, and has the additional merit that the field strength is not affected by changes in voltage occurring on the main circuit, which would tend to aggravate the variations. It also has the difficulty that the exciting dynamo or battery is comparatively small, and may therefore be weak and unreliable. An accident to it would incapacitate as many generators as were being charged by it. In a three-wire system the shunt field circuits of the dynamos on one side may be supplied with current from the other side of the system, which practically amounts to separate excitation, except that an extra generator is not required. But if any trouble occurs on one side it is likely to affect both sides of the system.

In the method of excitation devised by Mr. W. I. Donshea,* and represented in Fig. 32, one terminal of the shunt field winding *S* leads to one of the brushes *C*, while the other end is brought through the regulating rheostat *R* to the blade of the field switch *F*. This blade is pivoted on the same axis as the main dynamo switch *M*, but the two are not electrically connected together. The other main switch, *N*, and field switch, *F*, are first closed, *M* being left open. This completes the field circuit so that it is excited from the 'bus bars $B+$ and $B-$ as shown. When the

* *Electrical Engineer*, N.Y., Jan. 22, 1896.

dynamo is regulated to the proper voltage, the main switch *M* is then closed. On the blade of the latter there is a catch which engages with the blade of the field switch *F* and locks them together, also forming an electrical contact. When the main switch *M* is opened in order to throw the machine out of circuit, it brings the blade of the field switch with it, the two remaining in electrical connection; the field being now self-excited dies away gradually as the dynamo slows down. The switch *N* may then be opened in order to entirely disconnect the machine from the circuit. When the dynamo is required again, the catch that locks the two switches together is withdrawn, and the field switch is closed independently, the other steps having already been described. This method combines the advantages of self and 'bus excitation without involving complication. The 'bus bars $B +$ and $B -$ in Fig. 32 may be indefinitely extended in either direction; and any number of dynamos may feed current to them, the connections and operation being the same for each. If there happened to be no current on the 'bus bars, owing to accident or the stopping of all the machines, any one of them could be started as a self-exciting dynamo by closing the switches *F* and *M*.

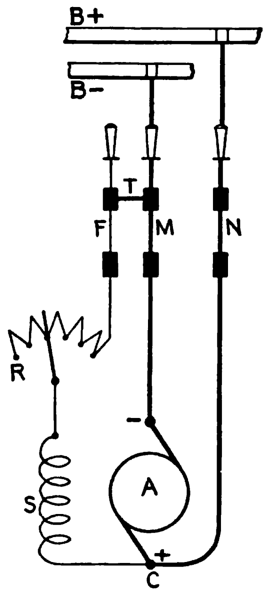


Fig. 32. Donshea Method of Shunt Field Excitation.

The excitation of a compound generator is conveniently and effectively accomplished by causing current from the other machines to flow through its series coil; for example, the switches *E* and *F* in Fig. 30 are first closed, as already explained. But a compound dynamo working alone would have to build up its own magnetism the same as a series or shunt machine. In the case of the last named, it excites more readily the higher the resistance in the external circuit, hence the latter should be opened if possible. But with a series or compound the excitation is facilitated by short-circuiting the main terminals so that a strong current will flow in the series field coils. This should be tried, however, only when the machine refuses to generate under normal conditions; and the

short-circuit should be carefully applied for brief periods, otherwise a very excessive current may be produced. The causes and remedies for a dynamo failing to generate are given in Vol. I., p. 362, and more fully in *Practical Management of Dynamos and Motors* by Crocker and Wheeler, p. 155.

Feeder Regulation. — It has been stated on page 51 that the ordinary practice in the smaller electric-lighting plants is to operate the generators at a fixed voltage, or to supply a somewhat higher voltage as the load in amperes increases, in order to make up for the drop in pressure on the conductors. The rise in voltage is produced by hand regulation, over-compound winding, or by an automatic regulator, as already described. In large systems of distribution the various feeders (Fig. 12) may differ greatly in length, and may be very unequally loaded, the latter condition being in a continual state of change. It therefore becomes necessary to independently control the different feeders, for which purpose several methods are employed, as follows: —

1. Connecting and disconnecting feeders at various points on the mains; 2. Feeder rheostats; 3. Auxiliary 'bus bars; and 4. "Boosters."

The first of these methods is represented in Fig. 33, in which a pair of mains, *P Q* and *R S*, are supplied with current from the

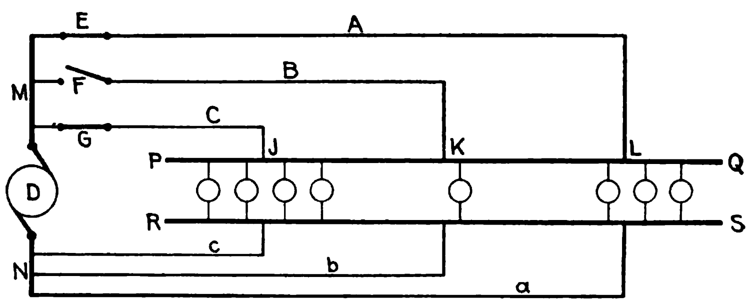


Fig. 33. Feeder Regulation by Disconnecting Feeders.

generator *D* by means of feeders *A*, *B*, and *C*, the corresponding return feeders being shown below. It is assumed that there are considerably more lamps burning at *J* and *L* than at *K*, hence the voltage would be higher at *K* than at *J* and *L*, if all three feeders were in circuit. This difference will be reduced by opening the switch *F*, thereby disconnecting the feeder *B*, as indicated. The

small amount of current required for the few lamps at *K* will be supplied from both directions by the feeders *A* and *C* with very little drop. If nearly all the lamps at *L* were turned out, the feeder *A* could also be disconnected by opening the switch *E*; but if every lamp were put in use, or if the load on the mains happened to be uniform, then all three switches, *E*, *F*, and *G*, should be closed.

The distribution of potential on uniformly loaded mains supplied by feeders at symmetrical points is illustrated in Fig. 34. Each of the mains *E K* and *S T* is supposed to consist of 1,800 feet of No. 2 (*A. W. G.*) copper wire, and supplies ten equidistant groups of lamps, each taking ten amperes. These mains are fed with current from the generator *D* by feeders *A* and *B*, which lead to points 400 feet from each end. The portion *EFG* of the mains

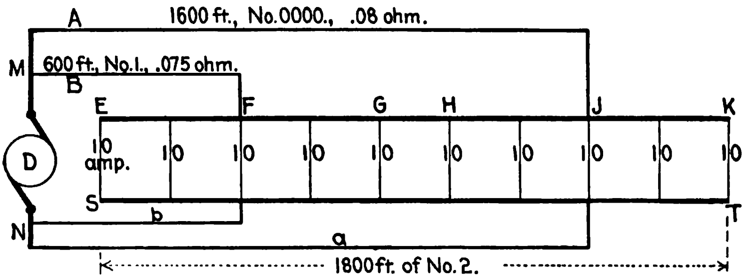


Fig. 34. Uniformly Loaded Mains and Uniformly Distributed Feeders.

is identical with the arrangement shown in Fig. 16, and so is the portion *HJK*; hence the distribution of potential will be the same as in that case, and is represented in Fig. 35, the highest pressure being 111 and the lowest 109 volts. With a perfectly symmetrical arrangement of the lamps, there will be no flow of current in either direction between *G* and *H*; hence those sections of the mains could be removed without affecting the electrical conditions. But in case there were more lamps at one end than at the other, then there would be a transfer of current through *GH*, which would tend to equalize the pressure. The feeder *A* is assumed to consist of 1,600 feet of No. 0000 wire having a resistance of about .08 ohm, and carrying 50 amperes; since it supplies 5 groups of lamps, each taking 10 amperes. The drop upon it is $50 \times .08 = 4$ volts, and the same amount for the return feeder *a*; consequently the potential at the generator *D* must be $111 + 4 + 4 = 119$ volts.

If the other feeder *B* consists of 600 feet of No. 1 wire, its resistance will be about .075 ohms, which is approximately the same, and would cause a similar drop. In this instance the resistances of two feeders are designed to be about equal by making their

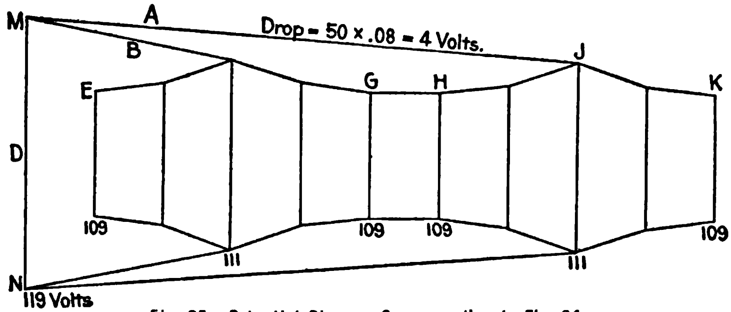


Fig. 35. Potential Diagram Corresponding to Fig. 34.

cross-sections proportional to their lengths. If the feeder *B* were made of the same size wire as *A*, the drop upon the former would only be $\frac{600}{1600} = \frac{3}{8}$ as much, or $1\frac{1}{2}$ volts, in which case it should be supplied with $111 + 1\frac{1}{2} + 1\frac{1}{2} = 114$ volts instead of 119, and one of the following methods of feeder regulation would be required. The same statement applies if the currents in the feeders differ considerably when their resistances are approximately equal.

Feeder Regulation by Resistance. — In such cases a feeder rheostat, or "feeder equalizer," consisting simply of a variable resistance, may be placed in series with each feeder, as represented in Fig. 36, the current capacity of the rheostat being sufficient for the maximum current conveyed by the feeder. In operating such a system a certain amount of resistance *R* is introduced into the circuit of feeder *A* that is lightly loaded, in order that the pressure which it supplies to the mains shall not be too high compared with that of the more heavily loaded feeder *B*, which has less resistance inserted. Thus by adjusting the arms of the rheostats *R* and *S*, the voltage at the ends of the feeders *A* and *B* may be made equal for all loads, or the potential at the outer end of *B* may be raised a little above that of *A*, in order to make up for the greater drop in the mains at *H* than at *F*.

The voltage at the farther ends of the feeders may be determined by running extra conductors, *WW*, called "pressure wires," from the generating-plant to the point at which the feeder is con-

nected to the mains. The actual potential is read directly on the voltmeter *V*, since the current in the wires *W W* is so little that there is no appreciable drop upon them even when they are quite small. Another method consists in subtracting the drop $I\ R$ on the feeders from the voltage *V* at the generators; that is, the potential at the ends of the feeders $P = V - I\ R$, in which *I* is the current and *R* the resistance of a given pair of feeders. For this purpose an amperemeter may be put in series with each pair of feeders, and it can be calibrated to give the drop upon them by simply multiplying its scale numbers by the total resistance of the two feeders. A still more perfect device is the so-called ***compensated voltmeter***. This has the ordinary coil which measures the voltage of the generators, and an additional coil that carries a cer-

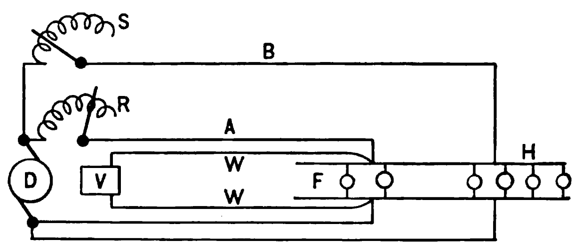


Fig. 36. Feeder Regulation by Resistance.

tain fraction of the feeder current, the effect of the latter being to slighty oppose the former, so that it reduces the deflection of the pointer, and indicates the pressure at the outer end of the feeder. The objection to the resistance method of regulation is the loss of energy that it entails, the amount of which is represented by the percentage that the voltage supplied to a given feeder is lowered. The present practice tends toward the use of the two following methods of feeder regulation in preference to the two already described, particularly in the larger systems.

Auxiliary 'Bus Bars are often employed in stations or plants of considerable size, in order to avoid the loss of energy which inevitably occurs when "dead" resistance is used for regulation. This method is represented in its simplest form in Fig. 37, *C* and *D* being two dynamos, one of which, *D*, is connected to the main 'bus bar *F*, and generates the ordinary potential required to supply the shorter feeders, or those that are lightly loaded, such as *B*.

The other dynamo, *C*, runs at a higher voltage, and is connected to the auxiliary 'bus bar *E* for supplying the longer or more heavily loaded feeders represented by *A*. The scope for regulation is still further increased by varying the pressure at either or both of the 'bus bars. This may be accomplished by hand or automatically, rheostats in the shunt field circuits of the dynamos, compound winding, or other means for controlling the *E.M.F.* of dynamos, being employed for the purpose. In this connection it should be

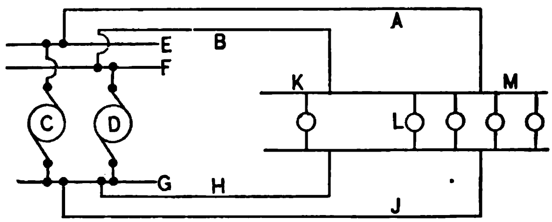


Fig. 37. Feeder Regulation with Auxiliary 'Bus Bar.

noted that the introduction of resistance in a shunt or separately excited field circuit involves far less loss of energy than when it is put in the main circuit, since the current in the former is only about one to three per cent of the latter. It is evident that any number of 'bus bars may be used, being supplied with current by dynamos running at different voltages; and two or more dynamos may be operated in parallel on any 'bus bar, in accordance with the demands for current. It is also obvious that several feeders may be connected to one 'bus bar. Each feeder is provided with switches that connect it to any particular 'bus bar according to the load upon it.

A Transfer 'Bus Bar is used to enable a feeder to be gradually shifted from one 'bus bar to another, without the sudden variation in potential which would occur if it were thrown over directly by means of the switches mentioned above. This arrangement is indicated in Fig. 38, being similar to that shown in Fig. 37, but having a transfer 'bus bar *P* in addition to the main and auxiliary bars *F* and *E*. The latter is connected to the resistance coils of a rheostat, the movable arm *V* of which is connected to the transfer bar *P*. The operation of shifting the feeder *B* from the main 'bus bar *F* to the auxiliary *E*, when its load becomes large, is as follows: The feeder *B* is connected to the transfer bar at *P*, the rheo-

stat *V* being previously open circuited. The arm *V* is then moved clockwise until it comes in contact with the extremity of the resistance. This connects the feeder *B* with the auxiliary bar *E* through the whole of the resistance, and allows a certain current to flow from *E* into *B*, the former having a higher potential than *F*, to which *B* still remains connected. The resistance is then gradually cut out by the further movement of the arm *V* until the current supplied from the auxiliary *E* to the feeder *B* is equal to the load carried by the latter, when the connection between *B* and the main 'bus bar *F* is opened. The remainder of the resistance is then cut out, which directly connects the feeder *B* with the auxiliary bar *E*, the transfer having been made without any disturbance of the system. In performing this operation the

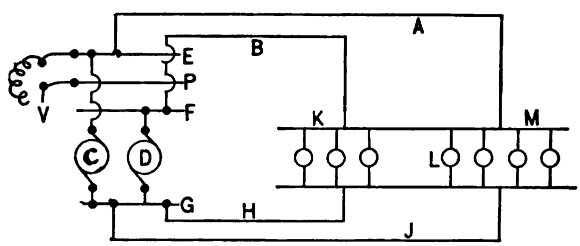


Fig. 38. Feeder Regulation with Transfer 'Bus Bar.

amounts of current may be ascertained by having an amperemeter inserted between the rheostat and *E* in addition to the amperemeter that should always be placed in circuit with each feeder. The difference of potential between the feeders, 'bus bars, etc., should also be indicated by voltmeters. The necessary instruments are assumed to be present in every case, but are omitted from the diagrams to avoid confusion, as they perform no active part in the operation of the system, their only function being to give information.

Where two or more feeders run to the same mains, one of them may be transferred from one 'bus bar to another by simply opening the switch connecting it with one bar and closing an instant later the switch that connects it to the other. Both switches must never be closed at the same time, as it would short-circuit the potential difference between the two 'bus bars. The drop on a feeder being usually only a few volts, its circuit may be opened

with practically no greater flash than is produced by any other circuit having a voltage equal to this drop, provided the remaining feeders and the mains are sufficient to carry the current without materially increasing the fall of potential upon them.

Feeder Regulation by Means of "Boosters" is represented in Fig. 39, in which *D* is the main dynamo generating the greater part of the electrical energy, and *R* and *S* are two small auxiliary dynamos called "boosters," connected in series with the dynamo *D* and the two feeders *A* and *B* respectively. Assuming that the main dynamo *D* generates a constant voltage, the variation in pressure required to regulate the feeders in accordance with the changing loads upon them is obtained by controlling the potential of the boosters *R* and *S*. This is usually accomplished by exciting the field magnets of the boosters from the dynamo *D*, a rheostat being

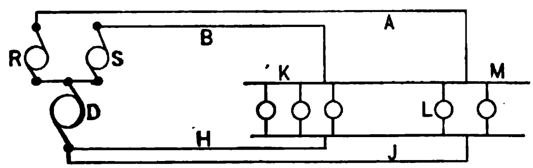


Fig. 39. Feeder Regulation by means of "Boosters."

inserted in each field circuit. Another plan is to provide the boosters with series-wound field magnets, in which case the voltage generated by each increases with the current flowing through it. With field magnets designed to work below magnetic saturation, this gives an automatic regulation that is almost perfect; since the extra pressure produced by the booster may be made to exactly overcome the drop on the corresponding feeder for all loads, or it may be designed to also make up for some or all of the drop on the mains and leads. The principle of this last-described method is quite similar to that of compound-wound dynamos; but it acts upon the feeders individually, instead of upon the system as a whole. It corresponds to a case where each feeder is supplied by its own compound generator, which is a possible but hardly practicable arrangement with a large number of feeders, twenty or thirty being an ordinary number. In any system the main generator and the boosters may all be driven by one or more steam-engines or other prime movers, or the boosters may be

operated by electric motors supplied with current from the main dynamos.

Similar machines are sometimes used to reduce or "crush" the voltage instead of raising it, in which case the main dynamo may be run at the average pressure required by the feeders, the potential in those that are heavily loaded being increased, and being depressed in the lightly loaded ones. A "crusher" which lowers the voltage by generating a counter *E.M.F.* acts as a motor, and tends to develop power; consequently, if it is coupled with a booster, it will drive the latter as a dynamo, provided that the energy absorbed by the former is slightly greater than that produced by the latter, in order to make up for mechanical and electrical losses in both machines. By thus arranging the machines in pairs, they run each other, and no external driving-power is needed.

Instead of having a separate booster for each feeder, as indicated in Fig. 39, two or more feeders requiring approximately equal voltages may be supplied from the same booster. In this way a large number of feeders may be regulated with only a few boosters, which are run at different potentials, the feeders being divided among them according to the extra pressure required. This is practically equivalent to a system having several auxiliary 'bus bars supplied with different voltages. In Fig. 37, for example, the dynamo *C* might be omitted, and the higher voltage required for the auxiliary bus 'bar *E* could be obtained by connecting a booster between *E* and *F*. This is often preferable; since it would only be necessary to run one main dynamo, the booster being driven by a motor fed with current from the dynamo.

The arrangement represented in Fig. 40 combines several of the methods of feeder regulation already described. The generators *C* and *D* operating in parallel are connected to the 'bus bars *F* and *H*, to which they supply the ordinary voltage required by the feeders. The conductor *E*, called the *high auxiliary* 'bus bar, is maintained at a higher potential than *F* by means of the booster *A*. The conductor *G* receives its current from the main 'bus *F* through the resistance *B*, consequently its pressure is less than that of *F*; and it is designated as the *low auxiliary* 'bus bar. The feeders *J*, *K*, and *L* are connected to *E*, *F*, or *G* according to the voltage that they require, the longest and most heavily loaded

being fed by the high auxiliary *E*, which is often 10 or 20 per cent and sometimes 40 or 50 per cent higher in pressure than the main 'bus *F*. The amount of this extra voltage is regulated by means of a rheostat in the field circuit of the booster *A*, usually excited from the 'bus bars *F* and *H*. If the dynamo *C* be connected to *E* and not to *F*, the higher pressure may be generated by it, and the booster *A* can be dispensed with, as already shown in Fig. 37; but it is often more convenient to operate all the main

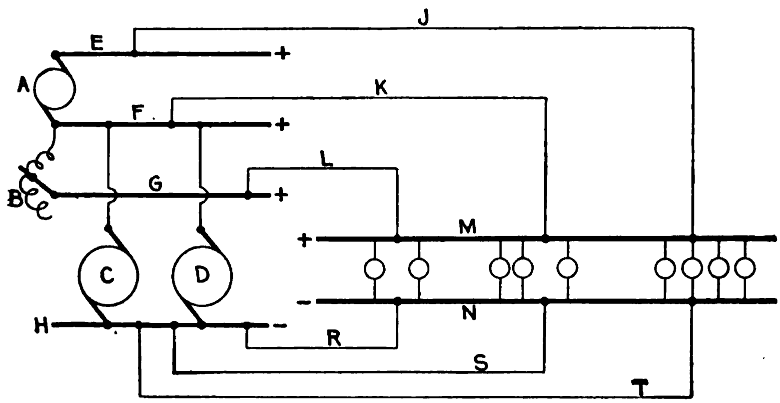


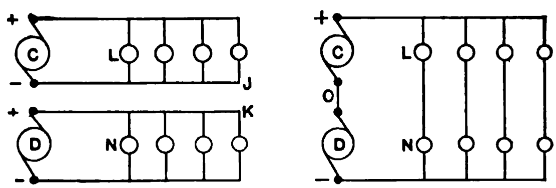
Fig. 40. Feeder Regulation by a Combination of Methods.

generators in parallel on the same pair of 'bus bars, and obtain the higher and lower potentials, if required, by means of boosters and resistances. The latter, on account of their simplicity, are applicable when the differences in pressure are small, the voltage of the low auxiliary 'bus *G* in Fig. 40 being between 5 and 10 per cent less than that of *F*, for example. But with greater reductions the loss of energy becomes too large an item, and it is more economical either to run another generator or a "crusher" (with *counter E.M.F.*) to supply *G*.

CHAPTER IV.

THREE AND FIVE WIRE SYSTEMS OF DISTRIBUTION.

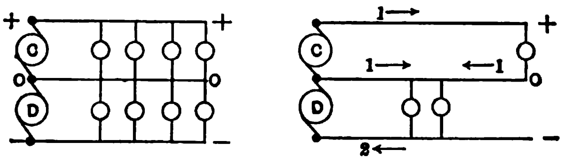
THE three-wire system, which was independently invented by Edison and Hopkinson, has for its object the saving of copper in distributing conductors. From the first introduction of electric lighting until about 1897, it was not considered practicable to use incandescent lamps designed for a pressure higher than 120 volts. This limited the potential at which parallel systems were operated, and demanded conductors of large size and weight, particularly when the current is transmitted any considerable distance, as already shown in the examples given. When it is attempted to supply incandescent lamps in series, difficulties immediately arise, due to the dangers of high potential, the interference between the lamps, and the imperfection of regulation, all of which were noted



Figs. 41 and 42. Evolution of the Three-Wire System.

in Chapter II. The principle of the three-wire arrangement may be understood by first considering two entirely distinct two-wire circuits, as represented in Fig. 41. If the lamps *L* and *N* happen to be placed in the manner shown, it is evident that they may be connected in series of two each, as illustrated in Fig. 42, in which case the intermediate wires *J* and *K* become superfluous and are omitted. But when one of the lamps is turned off or burned out, its companion will also go out; hence a third wire, indicated in Fig. 43 by a line marked 0, is extended from the junction between the two dynamos *C* and *D* in order to avoid the difficulty. This allows any number of the lamps to be disconnected without putting out

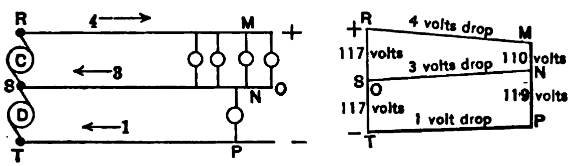
those which remain. The extra conductor is called *the neutral wire,* and is usually marked 0 or ±, the latter symbol representing the fact that it is positive with respect to one conductor and negative with respect to the other. The neutral wire carries no current if the system is exactly "balanced" (Fig. 43); but when the amounts of current on the two sides of the system are not the same, it supplies the difference, whatever it may be, as represented



Figs. 43 and 44. Three-Wire System.

by arrows and numbers in Figs. 44 and 45, each lamp being assumed to take one ampere.

It should be observed that the flow of current may be opposite in direction in different parts of the neutral wire (Fig. 44). Another peculiar condition in three-wire circuits is the fact that the potential at certain lamps may actually be higher than that of the dynamo on the same side of the system. This is demonstrated in the potential diagram (Fig. 46), corresponding to the arrangement



Figs. 45 and 46. Three-Wire System.

of lamps shown in Fig. 45. Assuming the resistance of each of the three wires to be 1 ohm, the drop on the + conductor between R and M will be 4 volts with a current of 4 amperes. The drop between N and S on the neutral wire will be 3 volts, since 3 amperes flow back through it. With a potential of 117 volts at each dynamo, this gives 110 volts for the lamps between M and N. The drop on the – wire between P and T is 1 volt, hence the potential of the point P is 1 volt above that of T; but as N is 3 volts higher in potential than S, it follows that the pressure be-

tween N and P is 2 volts greater than that delivered at S and T by the dynamo D. Therefore the lamps at $M\,N$ receive 7 volts less pressure, and the lamp at $N\,P$ is supplied with 2 volts more pressure than the potential difference at the respective generators. While this condition is possible, it is not likely to occur in practice, particularly in large systems, where the circuits are carefully balanced. In such cases, the difference in the total load on the two sides of the system is often as small as 2 or 3 per cent.

Advantages and Disadvantages of the Three-Wire System. — The sole merit of this arrangement is the fact that it saves copper, the amount of this saving being determined as follows: —

The circuit represented in Fig. 42 has two wires, while those in Fig. 41 employ four; hence the former requires one-half as much copper as the latter, assuming the size of the wires to be the same. Furthermore, the percentage of drop in Fig. 42 will only be one-half as great as that in Fig. 41, the explanation of this fact being given in Figs. 47 and 48, which show the distribution of potential in the two cases. In the two-wire circuits (Figs. 41 and 47) there will be a drop of 4 volts on each wire, assuming 4 amperes of current and one ohm of resistance for each; and the lamps will receive 106 volts with a pressure of 114 volts at the dynamos, the drop being $\frac{8}{114}$, or 7 per cent.

The lamps on the three-wire circuits (Figs. 42 and 48) receive 110 volts with the same initial potential, i.e., 114 volts, the drop being only $\frac{4}{114}$ or 3.5 per cent, which is one-half as much as in the previous case. It follows, therefore, if the wires in Fig. 42 have one-half the cross-section of those in Fig. 41, that the percentage of drop will be the same for both. Consequently Fig. 42 requires one-half as many conductors of one-half the size, or only one-quarter as much copper, as Fig. 41 for the same drop. If now the neutral conductor in the three-wire system (Fig. 43) be made the same size as each of the outside wires, the weight of the copper will be $\frac{1}{4} + \frac{1}{8} = \frac{3}{8}$ as much as in the two-wire circuits (Fig. 41) supplying the same number of lights at the same distance with equal drop. Since the neutral wire usually carries only a small current, it is often made (especially in feeders) one-half as large as either of the outside conductors, in which case the weight of copper becomes $\frac{5}{16}$ that demanded by the two-wire system.

The great saving in copper, amounting ordinarily to $\frac{5}{8}$ or 62.5

per cent, is considered of such paramount importance that the three-wire system is usually adopted in electric lighting for low-tension distribution wherever the distances are considerable. In the case of low-tension central stations this custom is very general, and even for large isolated plants the three-wire system is often selected. It is also employed in many instances for the secondary wiring in alternating-current distribution with transformers. The object in all cases is to save copper, which constitutes such a large item in the cost of nearly all electrical installations.

To offset this advantage, however, the three-wire system has the following disadvantages: —

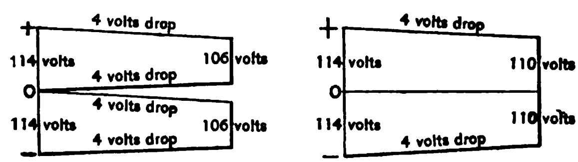
1. It is usually necessary to operate at least two dynamos or other sources of current.

2. It is necessary to lay and to take care of three wires instead of two.

3. The switches, cut-outs, measuring instruments, etc., are also more complicated.

4. The saving of copper stated, assumes that the neutral wire carries no current.

But if all the lamps happen to be in use on one side of the system only, the copper should be the same as for a two-wire circuit.



Figs. 47 and 48. Three-Wire System.

Even though the system be kept balanced as carefully as possible, so that the current in the neutral conductor is only 10 per cent of the total, the saving of copper would be reduced from 62.5 to about 50 per cent for the same actual percentage of drop.

5. The *variation* in potential may be aggravated by the increase that sometimes takes place (Fig. 46), which is impossible on a two-wire circuit.

When all these objections are considered, it is somewhat doubtful if the reduction in the weight of copper makes up for them in some cases where the three-wire system is adopted. There is a strong tendency on the part of the purchaser, consulting engineer,

and contractor to give too great weight to the matter of first cost, and too little heed to questions of convenience, labor involved, liability of accidents, and many other factors that make up running expense. The three-wire system is unquestionably more complicated and difficult to install or operate, and it should not be selected unless the saving that it secures is surely sufficient to pay for these disadvantages. For low-tension distribution to distances of a mile it has been considered necessary to employ it ; but for isolated plants, where the length of wires is only a few hundred feet, its superiority is by no means certain, in spite of the very powerful argument which may be based upon the saving of copper.

The improvements in and applications of 220-volt incandescent lamps render the three-wire system considerably less important than formerly, since it enables a two-wire circuit to be operated at 220 volts, the copper required being only two-thirds as much as for the ordinary three-wire system. To be sure the latter can now be run at 440 volts, giving it the same relative advantage as before ; in fact, such plants are now being installed in this country and abroad. Many five-wire systems are being changed to three-wire, with 220-volt lamps.

MODIFICATIONS OF THE THREE-WIRE SYSTEM.

Three-wire System with Double Dynamo. — Various arrangements have been used or proposed as substitutes for the ordinary plan of using two generators. One of these, outlined in Fig. 49, employs a double dynamo *D*, having two armature windings upon the same core, connected to two separate commutators *CC*. This double generator is used in the same manner as the two generators in Fig. 43, and may save floor-space as well as the trouble of running two machines, but no great advantage is secured.

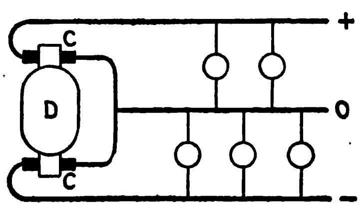


Fig. 49. Three-wire System with Double Dynamo.

Bridge Arrangement of Three-wire System. — Probably the first method of operating a three-wire circuit by means of a single generator was the bridge connection devised by Edison.* The plan

* U. S. Patent No. 343,017, June 1, 1886.

is indicated in Fig. 50, and consists simply in connecting a resistance *RR* across the outside conductors + and −, the neutral wire 0 being brought to a point on the resistance through the movable switch-arm *S*. The objections to this method are, first, the continuous loss of energy that occurs through the resistance *RR*, and second, the fact that the arm *S* must be adjusted for any change in load, in order to equalize the pressures on the two sides of the circuit.

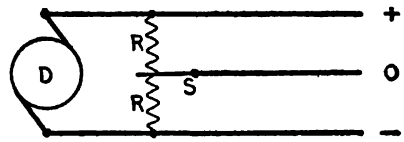
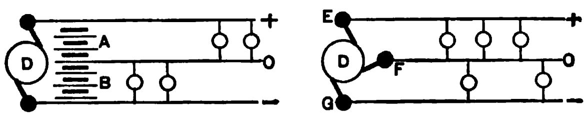


Fig. 50. Bridge Arrangement of Three-Wire System.

Three-wire System with Storage Battery. — This modification, illustrated in Fig. 51, requires only a single dynamo, *D*, generating the total pressure for both sides of the system, which is usually about 230 volts. A storage battery, *AB*, is connected between the two outside wires + and −, the neutral wire 0 being led to the middle point of the battery. In cases where it is advantageous to employ a battery to equalize the load on the engines, or for other reasons, this plan is a convenient one, since it only necessitates the running of one dynamo. The potential of the neutral wire 0 may be varied to make up for differences in load on the two sides of the system by shifting the point at which it is connected to the battery. If the difference of potential between the two outside conductors is greater than the *E.M.F.* of the battery, the latter will be charged, and *vice versâ*, the same as in a two-wire system. With a three-wire circuit it is also possible for one part, *A*, of the



Figs. 51 and 52. Three-Wire Systems.

battery to be discharging while the other part, *B*, is charging. This may occur if there are a great many lamps on the + side, and very few on the − side. The function of the battery is to act as an equalizer, taking or giving current, as required, and keeping the potential of the neutral wire approximately half way between the potentials of the + and − conductors. The fall in voltage during discharge and the rise during charge, amounting to

three-tenths of a volt or more, being nearly 15 per cent, and the difference between the charging and discharging pressures, make it necessary to employ extra cells and switching-devices, or means of regulation, such as are described in Volume I., page 397. A differential booster may also be used to automatically generate the extra voltage required to charge the battery.

The storage battery represented in Fig. 51 can be placed at a distance from the generator, and connected to it by two feeders, three wires being required only for the local distribution. This arrangement also enables the current on the feeders to be made more uniform, the battery being charged during periods of light load, and discharged when the demands for current are great. This permits feeders of smaller size to be used, and also reduces the variations in load on the generating plant, so that the latter operates more efficiently, and can be designed for less capacity than the maximum load. But extra expenses for attendance, rent, etc., are involved at the sub-stations.

Three-wire System with Three-brush Dynamo. — Fig. 52 indicates another three-wire arrangement that can be operated with only one generator, *D*, the neutral wire being connected to a third brush, *F*, placed half way between the main brushes *E* and *G*, to which the outside wires + and — are respectively attached. With most types of dynamo the brush *F* would spark excessively because it short-circuits the armature coils when they are generating the maximum *E.M.F.* There are several ways to avoid this difficulty, one of which consists in employing a four-pole dynamo, shown in Fig. 53, having two adjacent north poles, *N* and *N*, the other two being south poles, *S* and *S*. The machine thus becomes in effect a bipolar dynamo with each pole divided, the armature coils short-circuited by the brush *F* being in the space between the two halves *S* and *S* of the south pole, where they generate little or no *E.M.F.* A dynamo to be used in this way requires a field-magnet ring of sufficient cross-section between the *N* and *S* poles (i.e., at the top

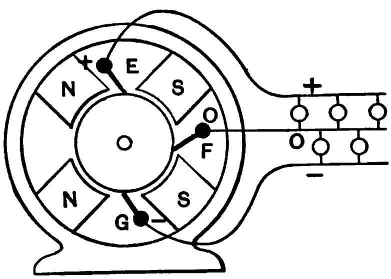


Fig. 53. Three-Wire System with One Dynamo.

and bottom in Fig. 53) to carry the total magnetic flux of one field core. In an ordinary multipolar machine with alternate *N* and *S* poles, this ring need have only one-half as much sectional area. Since practically no flux passes through the two sides of the field ring they might be greatly reduced in size, but this is limited by considerations of strength and appearance. The radial depth of the armature core must also be sufficient for the total flux of one field core. The extra quantity and less favorable disposition of material in the generator is not a very serious matter, however; and this plan of operating a three-wire system would often be a very practical and convenient one for small plants.

There is, however, with this arrangement, the difficulty that armature reaction tends to increase the flux in the lower *S* pole, and reduce it in the other, hence with heavy loads the voltage on the + side of the system would be less that on the – side. This can be counteracted by compound winding on the upper *S* pole, and differential winding on the lower *S* pole. Another brush could be placed between the two *N* poles, and connected in parallel with *F*; but since the neutral wire only carries a comparatively small current, one brush would ordinarily be sufficient, the main portion of the current being supplied through the brushes *E* and *G*.

Dobrowolsky Three-wire System. — Another method of operating a three-wire system by means of a single dynamo invented by

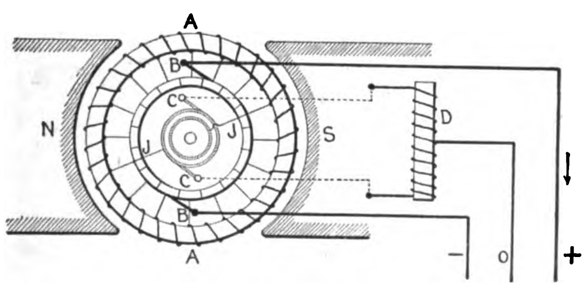


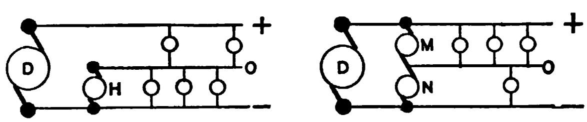
Fig. 54. Dobrowolsky System with Self-Induction Coil.

von Dolivo-Dobrowolsky * is represented diagrammatically in Fig. 54. It consists of an ordinary direct current generator, the armature *A* and pole pieces *N* and *S* of which are shown. A self-induction coil, *D*, is connected to two diametrically opposite points of the winding of the armature *A*. The coil *D* may be carried by and

* U. S. Patent, No. 513,006, Jan. 14, 1894.

revolve with the armature; but in the construction represented it is stationary, being connected to the armature winding through the brushes *CC*, rings and wires *JJ*. The middle point of the self-induction coil *D* is connected to the neutral conductor 0 of the three-wire system, the outside conductors + and – being supplied from the brushes *BB* in the usual manner. The *E.M.F* at the terminals of the coil *D* is alternating; hence the latter, on account of its self-induction, does not act as a short-circuit to the armature. Furthermore, the inductances of the two halves of the coil *D* being equal, the potential of the neutral wire 0 is kept midway between the potentials of the outside wires + and –. When the two sides of the system are unbalanced in load, the difference in current carried in one direction or the other by the neutral wire passes freely through the coil *D*, since the current is steady, or varies slowly, and is therefore unimpeded by the self-induction. It is evident that the ohmic resistance of *D* should be as low and its self-induction as high as possible, in order that the loss of energy and the difference in voltage on the two sides of the system shall be as small as possible under all conditions.

Three-wire System with Auxiliary Generator. — In the three-wire system represented in Fig. 55 the neutral wire 0 is connected



Figs. 55 and 56. Three-Wire Systems.

to an auxiliary machine *H* which supplies a potential one-half as great as that of the main dynamo *D*. The machine *H* acts as a generator when the – side requires more current than the + side, but it runs as a motor when the current on the + side is greater. Hence it should be belted to or directly coupled with the dynamo *D*, in order to save its power when acting as a motor. The machine *H*, being intended to carry only the difference between the currents on the two sides of the system, may have only 5 or 10 per cent of the capacity of the dynamo *D*. This is sufficient as long as the sides are fairly well balanced, but is entirely inadequate if the difference becomes great, which may easily occur by accident. The ordinary three-wire arrangement, or that shown in Fig. 52,

has the advantage of being able to operate, if necessary, with a full load on one side and none on the other, which might occur if there was an open circuit on one of the outside wires, due to the blowing of a fuse or to some other cause.

The same statements apply to the storage battery in Fig. 51, which may be designed to have a capacity equal to the full load or only a fraction of it.

Three-wire System with "Compensators" is represented in Fig. 56, in which the two auxiliary machines *M* and *N* are mechanically coupled together, and each generates one-half as much pressure as the main dynamo *D*. These machines are called *compensators* or *equalizers*, and serve to equalize the pressure and load, the one on the more lightly loaded side running as a motor, and driving the other as dynamo. Hence they are capable of operating with a difference in power on the two sides of the circuit equal to their combined capacity. When the system is perfectly balanced, both machines run as motors without load, and consume very little energy.

This combination involves three machines in place of the two dynamos required in the ordinary three-wire system; nevertheless, it is very commonly and successfully used, being in many cases decidedly preferable. The two machines *M* and *N* are entirely self-acting, driving each other mechanically and maintaining equal voltages, with very little attention or likelihood of trouble. They are in most cases more easily operated than a second dynamo, and the friction as well as other losses are usually less.

If both armature windings are upon the same core, armature reaction is neutralized, and the tendency to sparkling greatly reduced. A still more important advantage is the fact that the double machine *MN* can be placed at any desired distance from the generating plant and connected to it by two feeders, three wires being required only for the local distribution, as already stated in reference to Fig. 51. It is also possible to run a "booster" or small auxiliary dynamo by means of the compensating machines *M* and *N*, in order to raise the pressure of the circuit a certain amount, and make up for drop on the conductors. An arrangement of this kind, illustrated in Fig. 57, requires only one "booster," *B*, for both sides of the system. The compensating machines *M* and *N* are connected to the outside conductors at the points *R* and *S*

beyond the booster *B*, and therefore have the increased difference of potential, which they subdivide in two equal parts for the two sides of the system. The three machines *B*, *M*, and *N* are mechanically connected together by direct coupling or belting.

The field magnets in Figs. 55, 56, and 57 may all be excited by simple shunt winding connected to the brushes of each machine respectively. It is preferable, however, to feed all the field coils from the main current supplied by the generator *D*, since that makes each machine less likely to aggravate variations that occur in its own portion of the circuit. The shunt coils of the compensators *MN* in Figs. 56 and 57 may be connected in parallel or in series to the outside wires + and −. The field coils of the booster

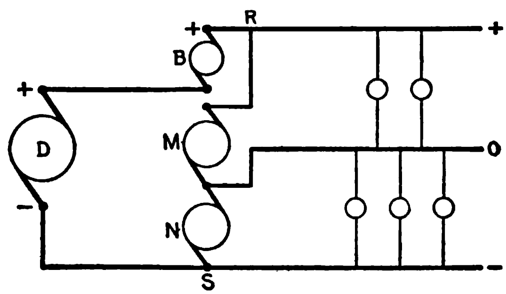


Fig. 57, Three-Wire System with Compensator and Booster.

B in Fig. 57 may also be fed from the main conductors + and −, in which case its voltage would be regulated by hand, using a variable resistance in the field circuit. If, however, it were provided with a series winding through which the main current of the + conductor passed, the extra pressure produced by it would automatically increase with the current as described in reference to feeder regulation in Fig. 39.

If the strength of the fields in the machines *M* and *N* (Figs 56 and 57) are capable of being independently regulated, the voltages on either side of the system may be varied to make up for differences in load, the pressure being made somewhat higher on the more heavily loaded side to counterbalance the greater drop on the conductors. This regulation can be made automatic by the arrangement represented in Fig. 58. The main generator *D* is assumed to be sufficiently over-compound wound to make up for the total drop on the conductors. Additional control of the vol-

tage may be obtained by adjusting the variable resistance *R* in the shunt field circuit. The compensating machines *M* and *N*, mechanically coupled as before, are also compound wound. The effect of the series field-coils *P* is to cause the machine on the heavily loaded side to produce a higher voltage, and the one on the more lightly loaded side a lower voltage, whereby the difference in drop is equalized. Assuming three lamps, each taking one ampere on the + side and one lamp on the – side, the dynamo *D* will supply two amperes, as indicated by arrows and figures, the machine *M* will generate one ampere additional, being driven by the machine *N* acting as motor, and using one ampere. The current in the series field-coils *P* increases the *E.M.F.* of *M*, and

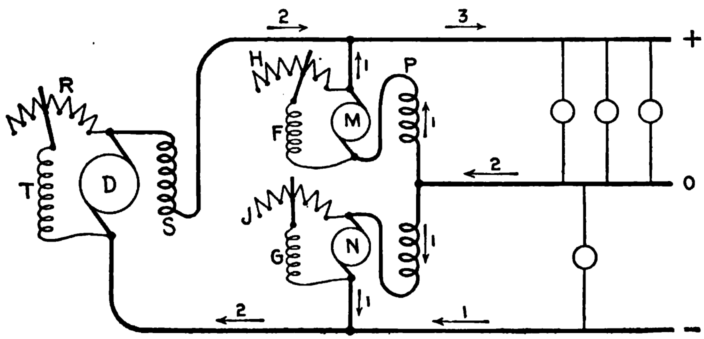


Fig. 58. Three-Wire System with Compound-Wound Boosters.

decreases the counter *E.M.F.* of *N*, since it flows in a reverse direction in the latter; hence the difference in drop on the wires between the compensator *MN* and the lamps may be equalized provided the compound winding is properly proportioned.

Conversion from Three- to Two-wire System. — A three-wire system of conductors can readily be connected so that it may be used as an ordinary two-wire circuit. For this purpose the two outside wires are connected to one terminal, and the middle wire to the other terminal of the generator, as represented in Fig. 59. The lamps are fed between the middle conductor and either of the others, but the direction of current is reversed in all of those that are on one side of the system. This makes no difference in the operation of incandescent lamps, but would require the connection of arc lamps to be reversed, the same being true of storage

batteries, electroplating cells, or other electro-chemical apparatus that may be on that side of the system. Some forms of meters, and other measuring instruments, would also be reversed in action. Motors running on either side of the circuit would not be affected, since the direction of rotation is not changed by reversing the current in both armature and field coils. But a motor or other device connected across the outside wires, which is the usual arrangement for the former, would receive no current, because these wires are of practically the same potential when used in this way.

The drop on the conductors is greatly increased by conversion to the two-wire arrangement. In a perfectly balanced three-wire system there is practically no current or drop on the middle wire; but when used as a two-wire circuit, the current and drop on this conductor is twice that in either of the others, consequently the total drop is three times as great as before. This assumes that the middle wire is the same in size as either of the others. If it is only one-half as large, then the drop in it would be four times as great as in one of the outer conductors, and the total drop five times as much as in a balanced three-wire system. There is also danger of blowing the fuses on the middle wire, or overheating it, unless it is specially designed to be used in this way.

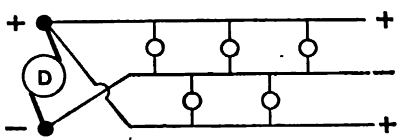


Fig. 59. Conversion from Three-Wire to Two-Wire System.

There are two cases in which the conversion from the three- to the two-wire system is commonly practiced. First, a small station, or isolated plant, which is operated on the three-wire plan when heavily loaded, and on the two-wire plan for light loads, one dynamo being sufficient in the latter case, and the drop on the conductor then being quite small. Second, an isolated plant, which is supplied by its own generator most of the time, but is connected to the three-wire "street circuit" (i.e., central station conductors) during certain portions of the day or night, or in case its machinery is disabled. On account of the latter contingency the name "breakdown switch" is applied to the device which connects the wiring inside the building with the outside conductors. This switch may be so made that it simultaneously opens the connections with the local generator.

OPERATION OF THREE-WIRE SYSTEMS.

The general arrangement of three-wire feeders and mains may be made substantially the same as already described for the two-wire system, the same methods and care being used in regulating the voltage. The feeders may consist of three conductors of the same size; but usually the neutral feeder is made ½ or ⅓ as large as either of the others, and if storage batteries or equalizing machines are placed at the outer ends of the feeders, the neutral conductor may be omitted, as previously explained (Figs. 51 and 56). For the mains and leads the three wires are generally made the same in size. The important point in connection with the three-wire system is the necessity for carefully *balancing* it; that is, keeping the currents on the two sides approximately equal. To accomplish this the lamps and other devices requiring current are divided between the two sides of the system, so that the loads shall be as nearly as possible the same for full capacity or any fraction of it. For this reason all three wires should be carried to any point where energy is required, unless the amount is extremely small. This applies to every building, even though it contains only a few lamps, and in fact to almost every room that is to be supplied with current. In this way the chance of having any considerable difference in load is reduced to a minimum.

Nevertheless, it is possible that a great many lamps might happen to be lighted on one side of the system and very few on the other side, in which case the drop in voltage would have about twice its normal value for the larger number of lamps, while the pressure might be raised for the smaller number, as already explained (Fig. 46). The likelihood of this happening is small, however, particularly in large systems, provided the lamps are carefully divided in wiring them. In case many lamps are to be lighted at the same time, they should be controlled by three-pole switches, which connect them to the two sides equally, or they should be divided into groups that are thrown on the sides alternately.

It is not sufficient in a three-wire system to have equal numbers of lamps on the two sides, they must also be distributed in approximately the same manner. For example, with a group of lamps requiring 100 amperes connected between the + and 0

wires at one point and an equal load between the 0 and — wires some distance away, there would be a current of 100 amperes flowing on the 0 wire between those points. This involves considerable extra drop, although the system would appear at the generating station to be perfectly balanced. In practice this local unbalancing of the three-wire system is one of the chief causes of variations in voltage upon it, and should be made as small as possible by carefully distributing the load on both sides of the system. It is this fact which renders it desirable to carry all three wires to almost every place where current is required, even though a fair balance in the total load might be obtained by supplying buildings alternately from the two sides of the system.

Grounding the Neutral Conductor. — A question that has aroused much discussion is the advisability of purposely grounding the neutral conductor of a three-wire system. The two principal arguments in favor of this plan are: First, it practically limits the potential between any point on the system and the earth to about 110 volts; second, it reduces the drop on the neutral conductor, since the current can also flow through the earth. In regard to the first of these reasons, it is a fact that the potential of the positive wire may rise to 220 volts if the negative wire becomes grounded, or *vice versâ* when the neutral wire is insulated. But it can hardly be said that trouble would be avoided if the neutral were grounded, as an accidental ground connection on either of the other sides would make a short-circuit and blow the fuse, thus putting out the lamps on that portion of the circuit. To be sure this locates the trouble, and calls for immediate attention, which may be a simple, but is also a crude way to keep the circuits clear of faults. If an accidental ground connection exists on one of the conductors when the neutral wire is not grounded, no trouble results until another ground occurs on one of the other two conductors. In the meantime an opportunity is afforded to correct the fault before any interruption of service or difficulty of any kind is experienced.

Unfortunately it is very troublesome to detect and locate a ground connection even on a two-wire circuit, and still more so with three wires. Nevertheless, there are methods which will accomplish this result; and if these were more generally used, they would be found to afford reasonably practical and convenient

means of taking care of three-wire systems. But these methods fail; in fact, the problem is practically impossible to solve if the neutral wire is grounded. This matter will be discussed further in the chapter on Detecting and Locating Faults.

Regarding the second advantage of grounding the neutral conductor, it may be said that it is well enough to use the earth to reënforce the conductance of the circuit, provided no serious difficulty results. But it is found that great damage is done by electrolytic action on gas, water, and other kinds of pipes, if large currents are allowed to flow promiscuously through the earth. In the case of electric railways with overhead trolleys, it is necessary to allow the current to pass into the track, or else adopt the double-trolley system, which is complicated, and not considered practicable for general use. But even for the trolley system the tendency is to demand more perfect bonding of the rails, and the use of return feeders to reduce the stray currents. In electric lighting there is no necessity for intentionally grounding the circuit or any portion of it, but it is generally recommended for the secondary circuit of a transformer, as a safeguard in case the high-tension primary circuit accidentally connects with the secondary.

Insurance and fire department authorities have been vigorously opposed to grounding the neutral of a three-wire system, or, in fact, any part of an electrical circuit, their experience having led them to believe that it is the source of danger and trouble. This practice is not so strongly opposed at present, and is being more generally adopted, as nearly all central station officers would prefer to ground the neutral conductors.

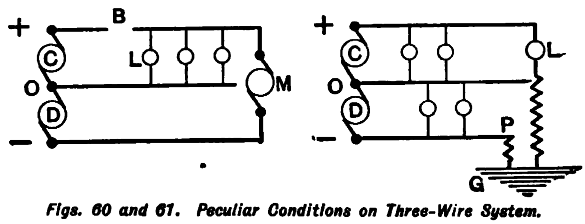
Peculiar Conditions on a Three-wire System. — The following cases may occur :—

1. The dynamo or dynamos on one side of the system may be accidentally reversed, so that both of the outside wires are positive or both negative. In that case a motor or other device fed by the two outside conductors will receive no current ; but lamps, etc., connected between the neutral and either of the outside wires, will have the usual voltage, which will be reversed on one side.

2. If one of the outside wires is open at *B*, Fig. 60, due to the blowing of a fuse or other cause, a motor, *M* (220-volt), beyond the break *B*, will receive some current at 110 volts through any lamps *L* that may be on the same side of the break as the motor,

and on the same side of the system as the break. These lamps will light up when the motor is connected, but the latter will have comparatively little power.

3. If the neutral wire is open, a motor or other device connected to the outside wires will act as usual, but lamps on one side



Figs. 60 and 61. Peculiar Conditions on Three-Wire System.

of the system will burn more brightly than those on the other side, unless the two sides are exactly balanced.

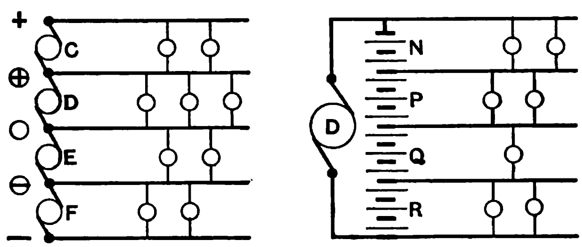
4. If one of the outside wires, Fig. 61, becomes grounded at *P*, a 110-volt lamp, *L*, or other apparatus, also grounded and connected to the other outside wire, will receive 220 volts, which is likely to destroy it.

FIVE-WIRE SYSTEMS.

The principle of the three-wire system may be extended, in order to effect a still greater saving of copper in electrical distribution. It would be possible, for example, to have a four-wire system requiring two-ninths as much copper as an equivalent two-wire circuit; but, for reasons to be given later, it has rarely, if ever, been tried. The five-wire system is employed in many places in Europe, but has not been introduced to any extent in this country. It may be operated with four dynamos, *C*, *D*, *E*, and *F*, as represented in Fig. 62; but the arrangements shown in Figs. 63 and 64 are more common. The second of these is similar to the three-wire system illustrated in Fig. 56, only one main dynamo, *D*, being required; and the total pressure generated by it, ordinarily about 440 volts, is subdivided by the four small equalizing machines or compensators, *J*, *K*, *L*, and *M*. These may consist of four separate machines mechanically connected together, or they may be made with all of their armature windings upon the same core and acted upon by one field magnet, in order to neutralize the effects of armature reaction. Fig. 63 shows a combination similar to the three-wire system represented in Fig. 51, a battery, *N*, *P*, *Q*, *R*, being utilized to

subdivide the voltage of the main dynamo *D*. The conductors are designated, as shown in Fig. 62, the two extra wires being called the "positive neutral" ⊕ and the "negative neutral" ⊖ respectively.

The comparative weight of copper required for the five-wire system may be determined by reasoning similar to that used in connection with the three-wire diagrams (Figs. 47 and 48). But it can be arrived at more simply by considering that the current in each of the outside wires of a perfectly balanced five-wire system is one-quarter as much as in a two-wire circuit supplying the same number of lamps. Hence the drop is only one-quarter as great, assuming the conductors to be of the same size. But since with five wires there are four sets of lamps in series, the *percentage* of drop is $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$ as much, or in other words, each conductor need be only one-sixteenth as large for the same percentage of drop. Therefore the two outside conductors of the five-wire system weigh one-sixteenth as much as those of an equivalent two-



Figs. 62 and 63. Five-Wire Systems.

wire circuit, and the five conductors weigh $\frac{5}{2} \times \frac{1}{16} = \frac{5}{32}$ as much, if all are made of the same size. By making each of the three intermediate wires one-half as large as each of the outside ones, the total weight is reduced to $\frac{1}{16} + \frac{3}{2} \times \frac{1}{32} = \frac{7}{64}$, or less than one-eighth as much copper as the two-wire circuit demands. The various results that have been obtained may be recapitulated as follows: —

COMPARATIVE WEIGHTS OF COPPER REQUIRED.

Ordinary two-wire system	1.000
Three-wire system, all three wires of same size	.375
Three-wire system, neutral one-half size	.313
Four-wire system, all four wires of same size	.222
Five-wire system, all five wires of same size	.156
Five-wire system, three inside wires one-half size	.109
Seven-wire system, all seven wires of same size	.097

It is evident that similar systems having a greater number of wires might be designed, but they would be extremely complicated, and of very doubtful advantage. In fact, the desirability of a five-wire system is questionable, since the use of 220-volt lamps enables three-wire circuits to be operated at 440 volts. A five-wire system calls for an even more perfect balance of load than is needed for three-wire circuits. This is secured by carefully dividing the lamps, etc., between the four parts of the system so that the loads may be as nearly equal as possible at all times. To this end all five wires should be carried wherever any considerable amount of energy is likely to be used, as represented at *A* in Fig. 64. If the demand for current is small, it is only necessary to run

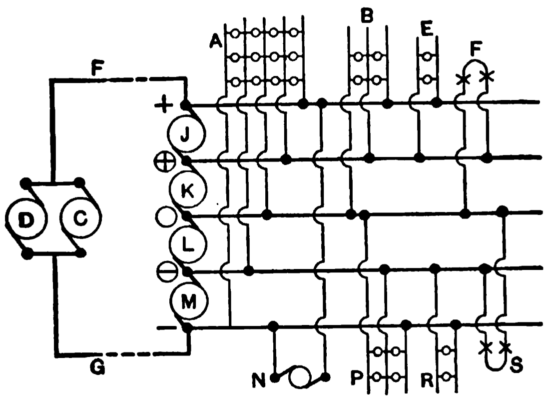


Fig. 64. Five-Wire System.

three wires, as shown at *B*. But in this case an approximately equal load, *P*, should be connected to the other side of the system, as near *B* as possible. For very small loads, *E*, *F*, *R*, and *S*, it may be allowable to put them on the separate parts of the systems, provided they are equally distributed, and not far apart, as represented. Motors should generally be supplied from the two outside wires (440 volts) as indicated at *N*; but if they are not large they may be connected to the + and 0 or to the 0 and – conductors (220 volts) at *B* or *P*, and very small machines, such as fan motors, may be connected to adjacent wires (110 volts) at *E* or *R*. Arc lamps may be arranged as shown at *F* and *S*, or a suitable number may be put in series across the outer wires at *A* or *B*.

The flow of the currents and values of the potential in five-wire systems may be determined by extending the methods already explained in connection with three-wire circuits. Although apparently a complicated matter, a problem of this kind can be solved without much difficulty in most cases. In practice the current to be supplied is usually known, or its probable value may be assumed. A diagram similar to Fig. 65 should then be made, showing the arrangement of circuits and distribution of current. It is much simpler, and in most cases sufficiently accurate, to consider the lamps or other apparatus requiring energy to be located in groups, approximating as closely as possible their actual positions.

This enables the conductors to be divided into sections, in each of which the current is uniform, as represented in Fig. 65. The

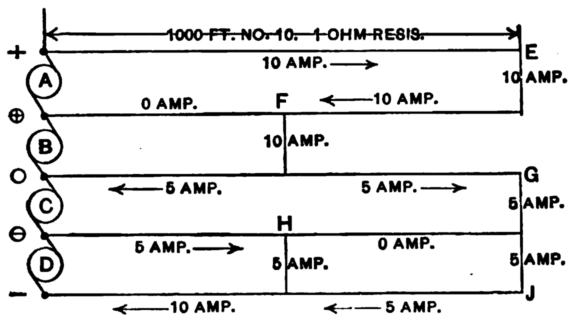


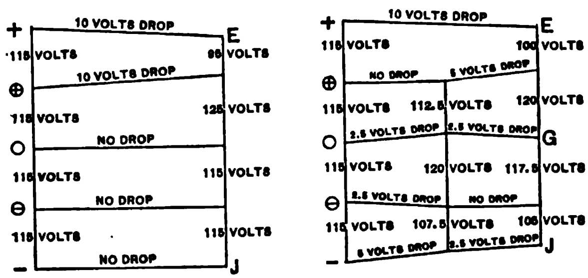
Fig. 65. Distribution of Current in Five-Wire System.

determination of the amount and direction of the currents in the various sections is easily made. If 10 amperes are required at *E* and also at *F*, it follows that that amount of current will flow out on the + wire, and half-way back on the ⊕ wire, there being no current in the rest of this conductor. Since 5 amperes are required at *G*, one-half of the 10 amperes will flow out to that point, and the other 5 amperes will return to the dynamo through the O conductor, the function of the three neutral or intermediate wires being to carry the *difference* between the currents used in the adjacent portions of the system, whatever its amount and direction may be.

The 5 amperes required at *H* are supplied by the ⊖ conductor, and the 5 amperes used at *J* by the same current that flows through *G*, hence there is no current in the outer half of the ⊖

wire. The currents from H and J return to the dynamo D by the — conductor as shown. In a similar manner the flow of current in any multiple-wire system may be determined, no matter how large or how small the loads on the different parts may be.

The next step is to determine the voltage at the various points, as indicated in Figs. 66 and 67. Let us first consider the case (Fig. 66) of 10 amperes being required at E, with no current used in the rest of the system. Assuming each conductor to have one ohm resistance, the drop on the + is 10 volts, and the same on the ⊕ wire, so that the lamps receive only 95 volts, the pressure at the dynamo being 115 volts. There will be no drop on any of the other three wires, since no current is drawn from them. It is interesting to observe that the potential difference between the extremities of the ⊕ and O wires will be 125 volts, as shown in



Figs. 66 and 67. Distribution of Potential in Five-Wire Systems.

Fig. 66. If three other groups of lamps were added, so that 10 amperes would flow directly across from E to J, the total drop would be 20 volts as before, 10 volts drop being transferred from the ⊕ to the — wire, and each group would receive 110 volts instead of 95, the aggregate number of lamps being four times as great. This brings out forcibly the advantage of a perfectly balanced five-wire system over a two-wire circuit, four times as many lamps being supplied with one-quarter as much drop for each.

With groups of lamps placed at E, F, G, H, and J (Fig. 67 corresponding to Fig. 65), the pressure is far from uniform, although the system is fairly well balanced in the number of lamps, but not in their position. This potential diagram is made by drawing from the five points marked +, ⊕, O, ⊖, and —, lines representing the pressure in the respective conductors and portions

thereof. By comparing Figs. 65 and 67 it will be seen that the direction of these lines is easily and definitely determined, the drop or slope of each section being equal to its resistance multiplied by the current flowing in it. In this connection it should be noted that the current in each group of lamps has been assumed to be constant, but it is evident that the group at *J*, receiving only 105 volts, will take less current than those at *G*, where the pressure is 117.5 volts. This fact might be allowed for by modifying the values of the current in proportion to the voltage; but the resistance of the lamps also varies, so that it would be very difficult to calculate the current that each group would take. In practice conductors are designed to supply a given current at a certain point; and slight variations in current due to changes in resistance, working conditions, etc., are not usually considered.

This may appear to be a somewhat rough method, but is not only justifiable, but practically unavoidable. In electric railway work, for example, the current required by a car varies greatly with the speed, grade, condition of track, load on the car, etc. Hence the only practicable plan is to assume a certain average current, or a certain maximum current, in designing the generating plant, conductors, etc. The average current corresponds to the ordinary working conditions, and the maximum current to the greatest possible requirements. The same is true for electric lighting, in which variations in the resistance of lamps are far less important than the changes in the number of lamps which are continually being made.

In practice the electric-light engineer considers the *initial voltage* at the generators, the *resistance* and *current* in each portion of the conductors which gives the *drop*, the latter subtracted from the initial voltage gives the pressure at the lamps. It would be an easy matter to calculate the resistance of the lamps by dividing the pressure they receive by the current flowing through them; but as a matter of fact one rarely, if ever, does this. It is only the inexperienced student who attempts to apply Ohm's law to the circuit as a whole. The practicing engineer confines it to determining the drop on the conductors, and usually considers one portion at a time, the drop in each being equal to its resistance multiplied by the current carried by it. The same is true in power transmission and distribution, including electric railway work. In fact it is

practically impossible to predetermine the resistance of the whole circuit except in very simple cases.

The author has examined five-wire systems in successful operation on a large scale in Paris and in Manchester, England. The difficulties encountered are not serious, and are apparently not much greater than with three-wire plants. Nevertheless, the increased number of conductors does involve more complication and possibility of accident. In the future the three-wire 440-volt system will undoubtedly be selected in preference to five-wire system.

Seven-wire System. — This is the next higher multiple-wire system that would be used, since it can readily be divided into two four-wire systems, or three three-wire systems, in order to supply current to individual buildings where it is not necessary to carry all seven conductors. Neither the four-wire nor the six-wire systems are capable of being conveniently divided into equal parts in this way; hence they are not to be recommended for adoption, except perhaps in some special case. The seven-wire system, with all conductors of the same size, requires 0.0972, or a little less than one-tenth as much copper as an equivalent two-wire circuit; but its complication is so great as to make it of very questionable desirability. Its design and operation would be similar to that of the three- and five-wire systems already described.

CHAPTER V.

DIRECT CURRENT TRANSFORMER SYSTEMS OF ELECTRICAL DISTRIBUTION.

THE fact that electrical energy can be readily transformed from a higher to a lower voltage, or *vice versa*, constitutes one of its most important advantages, and enables it to be conveniently and economically transmitted and distributed. The most prominent example of this method is the ordinary alternating current system, in which a high pressure of a thousand volts or more, generated by the dynamos, may be carried by small wires to a considerable distance, and there transformed to a low voltage that is harmless to persons and adapted to supply lamps, etc.

The direct current can also be transmitted in a similar manner, but it requires rotary machines instead of the simple induction coils or "static" transformers that are used for the alternating current.

Rotary transformers consist of a motor and a dynamo combined, the former being driven by the current from the main or *primary circuit*, and the latter generating the current for the *secondary circuit*, by which the lamps, etc., are supplied. It is obvious that the dynamo may be designed to produce any desired voltage without regard to that of the primary circuit. But in every case the watts —product of the volts and amperes—are less in the secondary circuit by an amount corresponding to the frictional and other losses which necessarily occur. This device has been given many names, such as dynamotor, motor-dynamo, motor-transformer, rotary-transformer, motor-converter, and rotary converter. The first of these has the advantage of being a single word, but has been objected to because the order in which the two machines work is inverted. This is not a serious objection, and the term is often used, being particularly appropriate to the construction in which the motor and dynamo are incorporated as one machine. In contradistinction the name motor-dynamo may be applied when there is a combina-

tion of two machines. The word transformer has been almost universally adopted for the induction coil or static transformer, so that the term converter, which was formerly applied to this device, is now free to be used for the machine in which alternating are changed into direct currents, or *vice versa*, in the same armature winding as shown in Fig. 71.

In dynamotors the two armature windings are placed upon the same core and are acted upon by the same field magnet, as illustrated in Fig. 68. This construction secures compactness, and also causes the armature reaction of the dynamo to practically

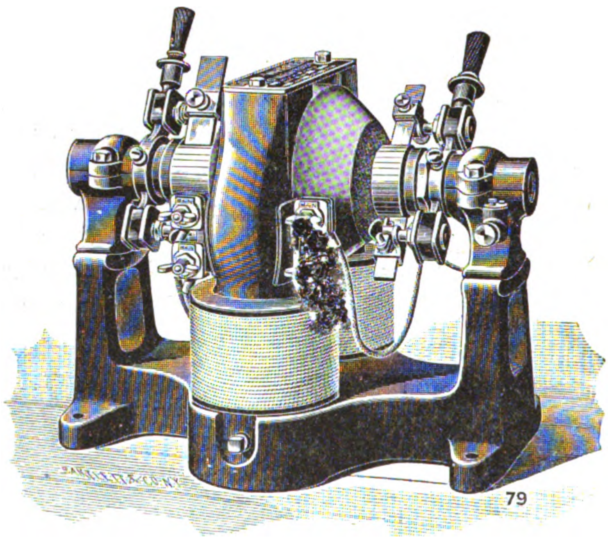


Fig. 68. Dynamotor, with Single Field.

neutralize that of the motor, thereby avoiding sparking and other troubles. But it is open to the objection that it is somewhat difficult to insulate the two windings from each other, and absolutely prevent the high voltage of one from breaking through to the other. Therefore this arrangement is not desirable where there are great differences in potential between the primary and secondary circuits, unless special precautions are taken. Another limitation of this construction is the difficulty of acting on the two armature windings independently for purposes of regulation. Since both are wound upon the same core and are under the influence of the same field, it is hardly possible to change the speed, magnetic

flux, or other conditions of one with respect to the other. In other words, the ratio of conversion, that is, the relation between the primary and secondary voltages, is practically constant, no matter how much the speed or flux may be varied. To be sure the difference of potential between the secondary brushes may be decreased by introducing resistance in the primary circuit, but this merely has the effect of reducing the available voltage supplied to the motor. The amount of this reduction is the drop $= IR$, in which I is the primary current and R the resistance inserted. A corresponding decrease in voltage is produced in the secondary circuit, but the ratio of conversion as measured at the brushes remains substantially unchanged. Resistance put in the secondary circuit will have a similar effect in decreasing the available potential, but in either case the loss of energy is considerable, its value in watts being I^2R. The so-called "regulation" is also seriously interfered with; that is, the available secondary voltage varies greatly with changes in the load, because any alteration in the current has a corresponding effect on the drop IR. Such a variation in pressure would usually be very objectionable; in electric lighting, for example, the voltage would fall as more lamps were added in parallel.

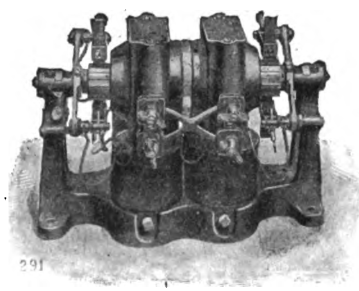


Fig. 69. Motor-Dynamo.

In order to secure independence of action between the motor and dynamo portions of a rotary transformer, the two armature windings should be carried by separate cores, each being acted upon by its own field magnet. This allows the field of the dynamo to be independently regulated, in order to vary the voltage generated. In fact, any of the well-known methods of dynamo regulation may be employed. For example, compound or over-compound winding applied to the dynamo field will give a constant or a rising pressure, with increase of current in the secondary circuit. In these cases the separate armatures may be mounted upon the same shaft, with only one pair of bearings, in the form shown in Fig. 69, or the two machines may be arranged upon the same base with an intermediate bearing, as represented in Fig. 70. If desired two

entirely distinct machines may be belted or directly coupled together. In fact, almost any motor and dynamo may be employed in this way, provided the former has sufficient power to drive the latter, and the mechanical connection is arranged to give the proper speeds.

It is evident that the motor of a rotary transformer may be designed to operate with an alternating current, and the dynamo to generate a direct current, or *vice versa*, in order to convert alternating to direct currents, or the converse.

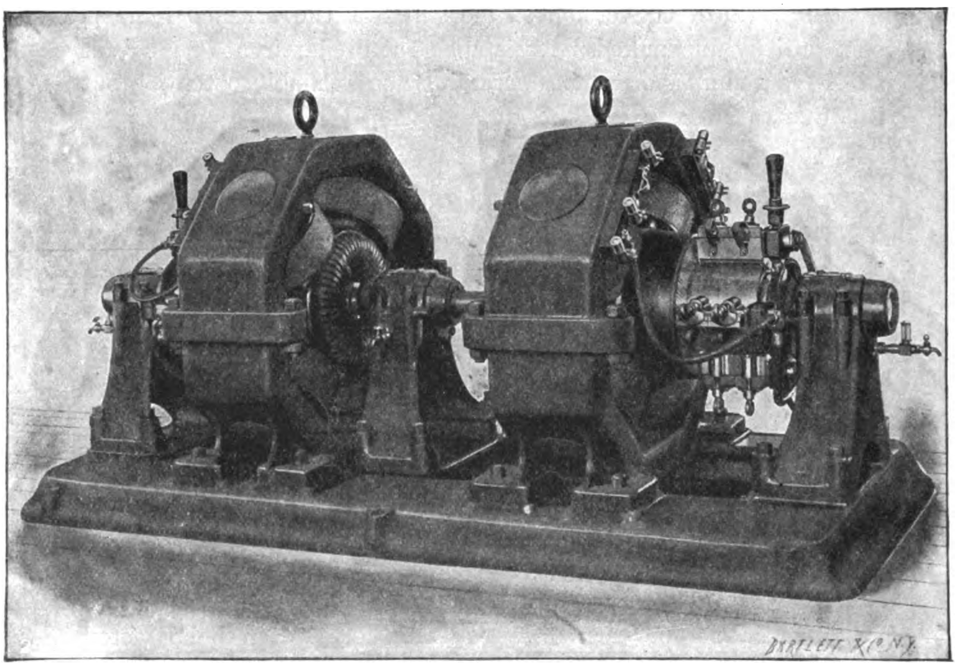


Fig. 70. Motor-Dynamo.

Still another type is the rotary converter, in which the same armature winding performs both the motor and dynamo functions. A simple form of this machine, shown in Fig. 71, consists of a ring armature, diametrically opposite points of the winding being respectively connected to two collecting rings. When the armature is supplied with direct current in the usual way by the brushes + and −, it will revolve as a motor, and an alternating current may be obtained from the brushes *A* and *B*. This action can be easily

understood when it is considered that, at the time indicated, the outer collecting ring is connected to the top or + point of the winding, and the inner ring to the bottom or – point of the winding, hence the current tends to flow from the brush *B* to the brush *A*; but when the armature has turned through 180 degrees, or half a revolution, these conditions will be exactly reversed, and the current tends to flow from *A* to *B*. Thus it is seen that an armature having only a single winding may be fed with a direct current, and will give out an alternating current. The ratio between the primary and secondary voltages is practically fixed in this form of converter, since the maximum value of the alternating *E.M.F.* is equal to the voltage of the direct current, as is evident from the diagram. With a true sine wave the effective value of the alternating *E.M.F.* is 0.707 of the maximum *E.M.F.*

If these machines are used to convert alternating to direct current, they are run as synchronous motors; hence they must first be brought up in speed by some extraneous power, or by operating them as direct current motors, until they are in synchronism with the alternating current by which they are to be operated.

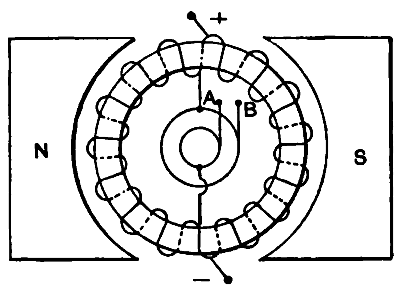


Fig. 71. Alternating-Direct Current Converter.

These machines are capable of exciting their own field magnets by the direct current which they generate.

By tapping the direct current winding at three or four points, machines are made for generating or utilizing three- or two-phase alternating currents respectively.

The actions of these machines are brought out in a paper by Professor R. B. Owens, and in the discussion which followed.*

Direct Current Transformer Systems of Distribution.—The usual arrangement of rotary transformers in electrical distribution is that represented in Fig. 72, being analogous to the ordinary alternating current system with static transformers. The current produced by the main generator *G* is carried to the machines by the conductors *A* and *B*, to which the motor portions *M* of the

* *Trans. Amer. Inst. Elec. Eng.*, July, 1897.

rotary transformers are connected in parallel. These motors are provided with shunt wound field coils that may be connected to the primary or to the secondary circuit, consequently the machines run at a practically constant speed. The dynamo portion *D* of the transformers are connected to the secondary circuits which supply the lamps, etc., *L*, as indicated. The field magnets of these dynamos may also be fed by the main circuit *AB*, or they may be self-excited by shunt or compound winding.

This system has the following advantages and disadvantages compared with the alternating current system. Rotary transformers are more complicated, cost more, require more attention, and are less efficient than static transformers. But it has been shown that they may be compound or over-compound wound, in order to supply a uniform or rising voltage, which is not practicable with static transformers. Furthermore, it is generally found that rotary

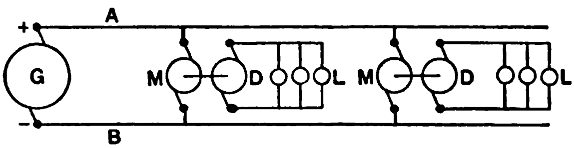


Fig. 72. Distribution by Rotary Transformers in Parallel

transformers are easily taken care of, and rarely get out of order. In many cases their use may be desirable or necessary, as, for example, in electrolytic, chemical, or metallurgical work, in arc lighting, in connection with storage batteries, or for other purposes for which direct currents are converted from alternating, or *vice versa.*

Rotary transformers may also be arranged as illustrated in Fig. 73, the motor parts *M* being all connected in series with the main generator *G*, and the dynamo elements *D* of the transformers being connected to the lamps, etc., *L*. If the current is kept constant (the generator *G* having a regulator like a series arc dynamo), and the motors *M* are simple series-wound machines, they will exert a certain torque, or turning effort, which will be constant. It follows, therefore, if the dynamos *D* are also series wound, that each will generate a certain current which will be constant. If lamps or other devices designed for that particular current are connected in series on the secondary circuits, the dynamos *D* will always maintain that current, no matter how many lamps there

may be. When lamps are added, the resistance of the local circuit is raised, and the current in it decreases, so that the dynamo increases its speed until it generates sufficient *E.M.F.* to produce practically the same current as before. Hence this constitutes a system which is self-regulating, when lamps, etc., are cut in or out of the secondary circuits. No harm results even when the secondary is short-circuited, since only the normal current can be generated. But if the secondary circuit is opened, then the machine will race, and probably injure itself by centrifugal force, because the torque of the motor *M* has its full value, and there is no load upon the dynamo *D*. To guard against this danger, some automatic device should be provided to short-circuit the field or armature of the motor when its speed or counter *E.M.F.* rises above

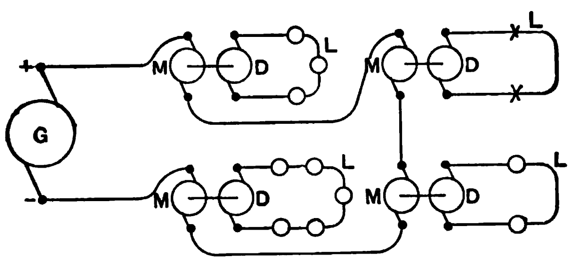


Fig. 73. Distribution by Rotary Transformers in Series.

a certain point. Another way to operate such a system would be to use motors *M*, with governors that maintain a constant speed for all loads, in which case the dynamos *D* should be shunt or compound wound, to feed lamps, etc., in parallel at constant potential.

Motor Dynamos as "Boosters" and Compensators. — The machines described in the present chapter for use in converting direct currents from one voltage to another are also applicable as "boosters" in feeder regulation, and as compensators in three- and five-wire systems of distribution. The motor-dynamo illustrated in Fig. 70 is well adapted to being employed as a "booster" in Fig. 39, for example. The left-hand machine could be driven as a shunt-wound motor by current obtained from the main generator *D* (Fig. 39), and the right-hand machine (Fig. 70) would serve as the "booster" *R* or *S* to raise the voltage in the feeders *A* or *B* (Fig. 39). The double machine shown in Fig. 70 or in Fig. 68

could also be used as a compensator to subdivide the total voltage in the three-wire system indicated in Fig. 56. Indeed, it is customary to use motor-dynamos for these purposes.

The Oxford System. — One of the most prominent examples of transmission and distribution by means of high-tension direct currents is the plant that has been in operation at Oxford, England, for several years. Similar systems are also used in London (Chelsea), Shoreditch, and other places in Great Britain, the name "Oxford System" being applied generally to this class of installations. They may be regarded as extensions of the simple arrangement shown in Fig. 72.

In the diagram, Fig. 74, which represents such a system, *D D* are the main generators supplying direct currents at 1,000 or 2,000

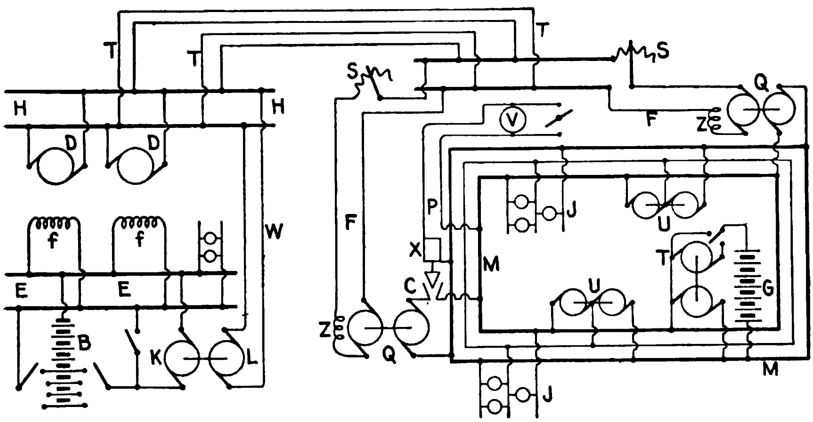


Fig. 74. High-Tension Direct-Current System.

volts to the high-tension 'bus bars *H H.* Their field coils *F F* are fed from the low-tension 'bus bars *E E,* that receive current at 100 or 200 volts from the secondary circuit of the motor-dynamo *K,* the primary *L* of which is supplied from the high-tension 'bus bars *H H* by the wires *W.* The storage battery *B* is also connected to the low-tension 'bus bars *E,* being charged by the machine *K,* in order to give current for lighting the station when all the generators (*D D*) are stopped, and also for exciting their field magnets in starting them. The current is carried from the high-tension 'bus bars in the generating plant over transmission conductors *T* to the two 'bus bars at the distributing station, that may be placed at a

considerable distance without involving large expenditure for the conductors, since the energy is transmitted at high voltage. From these 'bus bars, the high-tension current is conveyed by the pairs of feeders *F F* to the primary circuits of the motor-dynamos *Q* (located at sub-stations), the secondary circuits of which connect with the three-wire mains *M M M*, supplying the outside wires at about 200 volts.

The lamps *J J J* are fed from these three-wire mains in the usual manner. The motor-dynamos *Q* at the various sub-stations may either be controlled by attendants at the sub-stations, or they may be started and stepped from the distributing station by means of the starting rheostat *S* placed in each feeder circuit. In the latter case, the motor-dynamos are provided with series field coils *Z* in order to give magnetization for starting up, after which excitation is produced by a shunt winding (not shown) supplied from the secondary circuit. The latter is connected to or disconnected from the mains *M* by the switch *C*, that may be operated from the station by means of the magnet *X* and wires *P*. The latter also serve as pressure wires, the voltage on the mains being indicated in the station by a voltmeter *V*.

Compensators *U* are connected to the three-wire mains *M* at various points to equalize the voltage on the two sides of the system. These machines may be simple, like *M N* in Fig. 56, or they may be provided with series winding, as in Fig. 58, in order to raise the pressure on the more heavily loaded side when the system becomes unbalanced. The storage battery *G* is connected to the mains *M* for the purpose of supplying current during the day, or when the load is light, thus enabling all of the main generators *D D*, and motor-dynamos *Q Q*, to be stopped a considerable portion of the time. This battery is charged when the generating plant is running, the increased voltage required being produced by the booster *T*, or a differential booster may be used for the purpose.

If desired, the storage battery *G* may be employed to supply current for the "peak" of the load-curve (i.e., the short period of maximum load), thereby relieving the generating plant, the feeders *F F*, and the motor-dynamos *Q Q*, at the time of heaviest load. The battery may be charged when the load is lighter, so that this plan of working would tend to secure a uniform load on the machinery while running, and would also allow it to be stopped when the

load is very light. Storage batteries may be installed in the generating plant (as at *B*), in the distributing station, in sub-stations on the mains (as at *G*), or in all three places; the nearer they are to the lamps, the more of the apparatus and conductors they may relieve at times of maximum load. In fact, one of the advantages of this or other direct-current system is the ability to use storage batteries in connection with it. In some cases the distributing station may be omitted, the feeders *F F* being run directly from the 'bus bars *H H* in the generating station to the motor-dynamos *Q* in the sub-stations. The *Electrical World* (N. Y.) of March 12, 1898, contains a description of this system as used on a large scale at Chelsea, England, also the variable ratio direct-current transformers that are employed there. A description and illustrations of a more recent installation of this character at Bromley, England, are given in the *Electrical World and Engineer* (N. Y.) of Feb. 17, and in the London *Electrician* of January, 1900.

An important method of electrical distribution consists in transmitting the electrical energy by means of alternating currents, usually two- or three-phase, from the generating plant to stations at which it is transformed into direct currents by means of rotary converters, and distributed for lighting and other purposes. Such systems will be described after the principles of alternating currents have been considered.

CHAPTER VI.

NETWORKS OF ELECTRICAL CONDUCTORS.

THE most complete system of parallel distribution is that in which the conductors are interconnected to form a network. This arrangement was developed from the "feeder and main" method of Edison,* and is also due to him. It is used in most of the large systems throughout the world for low-tension, direct-current distribution, and is often employed for the secondary circuits of alternating-current transformers, especially where the system is a large or important one. The enormous networks of mains constructed by the Edison Electric Illuminating Companies in New York, Chicago, Philadelphia, Brooklyn, Boston, and other large cities, may be cited as very prominent examples. Networks are sometimes adopted in the interior wiring of buildings; but they are usually quite simple in such cases, being seldom developed much beyond the ring mains represented in Figs. 19 and 20, which may be regarded as the simplest form of network.

A two-wire network of conductors is indicated in Fig. 75, *A B C D* being composed of two sets of positive mains at right angles to each other, and connected at the points where they intersect; *E F G H* being a similar network of negative mains represented by dotted lines. The mains are supplied with current from the generating station *S* by feeders which are not shown in Fig. 75, because they would confuse the diagram. At any desired point a lamp will be fed with current if connected between the + and − networks. In fact, the case may be considered as equivalent to that in which two parallel sheets of copper are respectively connected to the terminals of a source of electrical energy, lamps being connected across from one sheet to the other.

Distribution of Current and Drop in Voltage in Networks. — In order to study the flow of current, let us consider by itself one-

* See page 30.

quarter of the positive network, and suppose it to be supplied at the point *J* by a feeder from the station *S*, as represented in Fig. 76. Assuming that the portions of the three horizontal and the three vertical mains included between the points *A* *Y* *X* and *Z* are uniformly loaded, and not considering the effect of any load outside of this region, it follows that one-quarter of the current will flow out from the feeding-point *J* on each of the four mains leading therefrom. If ten lamps, each taking one ampere, are connected to each section of the mains, the initial current in the main *J a* will be 30 amperes, since three sections (*J a*, *a A*, and *a Y*) must be supplied by it. When the current reaches the point *a*, it will have been reduced to 20 amperes, since 10 amperes are consumed in the sec-

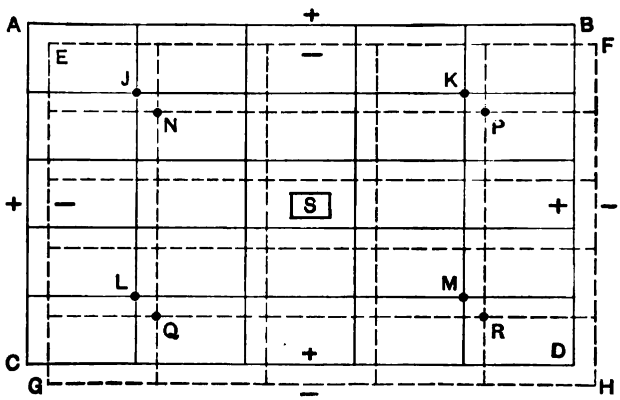


Fig. 76. Two-Wire Network for Parallel Distribution.

tion *J a*. Hence the average current between *J* and *a* is 25 amperes; and if the resistance for each section be taken as .04 ohm, the drop will be 1 volt. The initial current from *a* to *A* is 10 amperes, and its final value is zero; hence it averages 5 amperes, and the drop is .2 volts for that portion. The same is true of the section *a Y*, provided that the load beyond *Y* be ignored, as already stated. Having thus determined the drop in voltage on the positive mains, it is evident that precisely the same drop will also occur on the negative conductors. A lamp at *J* will receive the full pressure supplied by the feeder, which may be assumed to be 112 volts; a lamp at *a* will have 112 − (1 + 1) = 110 volts; and a lamp at *A* will be fed with 112 − (1 + 1 + .2 + .2) = 109.6 volts. Similar statements apply to the lamps at the other points, *W Z*, etc.

When the lamps are not equally distributed, the problem is much more difficult to solve. In the apparently simple case of a single lamp connected at *W*, a large portion of its current will flow directly from *J* to *W*, but a considerable fraction of it will take the path *J a Y W*, and also the path *J z Z W*. Since there is a flow of current from *J* to *A*, the latter must be of lower potential than the former; hence a small amount of current will take the course *J j A Y;* and if the network were extended beyond *A*, some current would follow still more indirect routes. Current would also pass through the remainder of the network shown in Fig. 75, as well as through the portion represented in Fig. 76; in fact, a single lamp connected at any point of a network would cause current to flow in every section except a few that might happen to have no potential difference between their ends. With a number of lamps irregularly located, the conditions become even more complex.

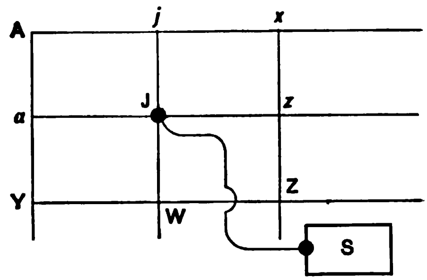


Fig. 76. Portion of Network Represented in Fig. 75.

It might be supposed that a solution of the problem could be obtained by comparing the resistances of the various paths. For example, the course *J a Y W* has three times the resistance of *J W*, hence the current in the former should be one-third as much as in the latter. But this is not true, because *J j A a* is in parallel with *J a*. If we attempt to allow for this by calculating the joint resistance, the case is further complicated by the fact that the section *J j* carries current that flows *via X* as well as through *A*, and so on. A correct method would consist in applying Kirchhoff's Laws, which are as follows:

1. *The algebraic sum of the currents in all the conductors that meet at any point is zero.*
2. *The algebraic sum of all the products of the currents and resistances in conductors forming a closed loop equals the algebraic sum of all the E.M.F.s in the loop.*

In the networks under consideration there is usually no E.M.F. working within each loop, as, for example, the loop *J a Y W*; therefore we may simplify the second law as follows:

The algebraic sum of all the products of the currents and resistances in conductors forming a closed loop is zero.

The application of these principles to simple cases has already been given on pages 35 and 49; but it would be difficult to apply them to the extensive and complicated networks used in practice, particularly when the lamps are unequally distributed. Nevertheless, methods for making such calculations have been given by Herzog and Stark,* Herzog,† Coltri,‡ Muellendorff,§ and others.

Electrical Model of Network. — In the pioneer work of Edison in 1882, the designing of the underground network of conductors was aided by constructing models in which the conductors were represented in miniature by copper wires. If the model is correct in scale, it is possible to determine from it the distribution of current and drop with various amounts and positions of load. This plan can be followed in any case, but would ordinarily be considered too much trouble, although it might often effect a considerable saving in, or better arrangement of, the copper.

Mechanical Model of Network. — Another method of solving this problem was devised by H. Helberger ‖ of Munich, and consists in employing a mechanical model in which the conductors are represented in length and position by horizontal strings stretched with a certain force corresponding to the cross-section of the conductor, the load being applied in the form of weights that are hung upon the strings, and are proportional to the current consumed at the various points. The amount that the strings are depressed indicates the drop in voltage, being usually limited to a certain value in a given case. The points at which the strings are supported correspond to the feeding-points, being raised or lowered with respect to each other a distance proportional to the difference in the electrical pressures with which they are fed.

Actual Design of Network. — These methods for determining the size of the mains in a network are not much used in America, although they are applied quite generally in Germany. Experience

* *Elektrotechnische Zeitschrift*, 1890, p. 221, and *Electrical World*, vol. xv., p. 300.

† *Elektrotechnische Zeitschrift*, 1893, p. 10.

‡ *Ibid.*, 1893, p. 425.

§ *Ibid.*, 1894, pp. 67 and 236.

‖ German Patent No. 68918, Class 21, April 5, 1892. See also *Western Electrician*, April 27, 1897.

in this country has shown that it is sufficient to employ a few standard sizes of mains. In New York City, for example, each of the three-wire mains has a cross-section of 350,000 circular mils in the central and heavily loaded portions of the network, and a cross-section of 200,000 circular mils in the outlying or less heavily loaded districts, and in some cases conductors of 150,000 circular mils are large enough. It is not found necessary to specially determine the size of each individual main or section thereof; the same size being used throughout a large district, and having been selected with reference to the general rather than local conditions.

The justification for this apparently crude practice is, first, the simplicity of laying and maintaining a network composed of only two or three standard sizes of mains, larger or smaller sizes being either too clumsy or too weak mechanically; second, it is practically impossible to predetermine the current that a main will carry, the demand upon it being often much greater or less than was expected; third, an excess of copper in one portion of a network tends to help other portions that are more heavily loaded, and conversely a small section of main acts as a weak link in the chain.

It is important to appreciate this interdependence of the parts of a network of conductors, as it constitutes its chief advantage. In the mechanical model already referred to, it is evident that all of the strings would aid each other in supporting a weight hung at any point upon them. The electrical analogue acts in a similar manner.

As already stated, it is customary to construct networks with certain sizes of mains which have been found by experience to be suitable for towns having a certain density of population, character of service, etc. In cases where this very empirical method cannot be followed, or when it is desired to check it by calculation, a careful plan of the given district should be made, and lines representing the proposed mains are then drawn. A main (2- or 3-wire as the case may be) is run through each street, or two mains may be laid, one on each side, in order to reduce the trouble of making house connections. In the case of unimportant streets in which there are no customers, the mains may be omitted or put in later. Where the mains intersect they are connected, all the + conductors (of which there are usually four or eight) being brought to-

gether, the same for the − conductors, and also for the ± conductors in a three-wire system. The connection of four + wires and four − wires in a two-wire system is represented at *J* and *N* in Fig. 75. Having thus laid out the entire network, certain feeding-points are then chosen. There is no absolute rule for determining their position, but they should be located to give as nearly uniform voltage as possible throughout the system. They should be arranged so that the feeders can be run conveniently to them and connected to the network, and should be nearer together where the load is great, and *vice versa.* In case it is subsequently found that they are too far apart, others may be added without disturbing the feeders and mains already laid. In this way increase of load upon the system may be provided for at any time. It is also possible to reënforce the mains by laying others parallel to them, but practically the same result is obtained when additional feeders are put in. If, for example, the average distance between feeding-points is reduced to one-half, the average current on a given main will also be one-half as great as before, and since it flows only one-half as far, the drop would be one-quarter as much. Extending a network of mains in any direction will also tend to help the conductors already laid, because it provides more paths for the current, as explained on page 104.

The Edison system of underground conductors originally adopted for network distribution and still very generally employed for the purpose will be described in the chapter on Underground Conductors. Other methods of constructing such networks will be given under the same heading.

CHAPTER VII.

PRINCIPLES OF ALTERNATING CURRENTS.

Introduction. — The various principles and facts concerning direct current distribution set forth in the preceding chapters, apply also to alternating current systems. But in addition to the simple phenomena due to resistance, which occur in the former case, there are certain *additional* factors that must be considered in connection with alternating current transmission. The flow of a direct current, which is steady, is entirely determined by the *ohmic resistance* of the various parts of the circuit; and if all these resistances are known the distribution of potential and current can be determined exactly. The flow of an alternating current depends not only upon the resistance, but also upon any *inductance* (self or mutual inductance) or *capacity* that may be contained in or connected with the circuit. These two factors have absolutely no effect upon a direct current after a steady flow has been established, which usually requires only a small fraction of a second. But in an alternating circuit either or both of them may be far more important than resistance, and in some cases may entirely control the action of the current, the effect of resistance being insignificant.

Since alternating current problems involve a consideration of three factors, they are usually more complicated and difficult to solve than those relating to direct currents. Nevertheless, by an extension of the principles and methods already explained, it will be found that alternating current systems can be designed correctly and without great difficulty.

Practically the only reason for employing alternating currents in electric lighting is to enable the cost of the conductors to be reduced by using high voltages and transformers. It has already been shown that the cross-section of a wire needed to convey a

given amount of electrical energy in watts, with a given percentage of "drop" or loss of potential in volts, is inversely proportional to the square of the *E.M.F.* employed: hence it requires a wire of only one-quarter the cross-section and weight if the initial voltage is doubled. The great advantage thus obtained by the use of high tension can be realized either by a saving in the weight of wire required or by transmitting the current to a greater distance with the same weight of copper. In alternating current electric lighting the primary *E.M.F.* is usually at least 1,000 and often 2,000 to 10,000 volts. Even at a pressure of 1,000 volts an advantage of 100 to 1 is gained over a system operating at 100 volts. This enormous difference enables a given number of lamps to be supplied at a far greater distance, and at the same time the conductors weigh very much less. These facts make it unnecessary to design a system of alternating current conductors with the great care that is required for direct current distribution, since the use of slightly larger conductors will make up for any small differences in the arrangement of the feeders and mains. The result is that ordinary alternating current systems of conductors are less complicated than those used for direct currents. The very elaborate network of mains, for example, often employed for the latter is seldom required for the former except in the low voltage secondary distribution.

On the other hand, the actual uniformity of voltage secured in direct current circuits is usually superior to that obtained on alternating current systems. This is partly due to the fact just stated, that less care is required in designing the circuits, consequently there is a tendency to exercise too little care. The difference also arises from the effects of inductance and capacity, which produce variations in potential as great as, or greater than, those due to resistance alone. The exact influence of these factors under various conditions will be considered later.

The reason that the alternating current can be used at the high pressure of 1,000 volts or more, while the direct current is limited to about 110, 220, or 440 volts for constant potential lighting is due to the greater facility with which the alternating current can be *transformed* from a higher to a lower pressure, and *vice versa.* This is accomplished by simple transformers, consisting merely of two or more coils of wire wound upon an iron core. Since there are no moving parts, the attention demanded and the likelihood of

the apparatus getting out of order are small. This enables the alternating current to be generated at or transformed to a high pressure suitable for transmission over long distances with small conductors, the potential being locally transformed to that required by the lamps, usually about 100 volts. In order to convert a direct current from one potential to another it is necessary to employ a motor-dynamo, which is practically a combination of a motor and a dynamo costing considerably more than an alternating current transformer, having a lower efficiency, and being more troublesome to take care of. In almost every other respect the direct current is preferable for electric lighting; and where the distances are not great, as, for example, in isolated plants and central stations in thickly populated cities, the direct current has been the system most generally and successfully employed.

Two-phase and three-phase alternating current systems are often employed to supply incandescent and arc lights; but they are only advantageous for operating motors or rotary converters, and so far as lamps are concerned, they are more complicated, and possess no compensating superiority over the single-phase system. The latter, on the other hand, is not desirable when there are a number of motors of anything more than small size, such as fan motors. Hence polyphase systems are used in cases where both lamps and motors are to be supplied with alternating currents.

The principles of alternating currents will now be given; but it is not intended to treat the subject exhaustively, as there are several excellent works entirely devoted to it. It is sufficient herein to consider briefly the chief facts, to serve as a basis for study and calculations concerning alternating current lines, transformers, etc.

Principles of Alternating Currents. — Each armature coil of a dynamo tends to generate an *E.M.F.*, which rises to a certain maximum value, then falls to zero, then reverses in direction, and again returns to zero. This cycle of changes, which can be represented by a curve (Fig. 77), constitutes a complete *period;* and since it is repeated indefinitely at each revolution of the armature in a bipolar field, the currents produced by such an *E.M.F.* are called *periodic currents.* The number of complete periods in one second is called the *frequency* of the pressure, or current. In Fig. 77 the period is completed in .01 second, hence the frequency is 100. Since the

current changes its direction at each half-period, it follows that the number of *alternations* or reversals is twice the frequency.

Various forms of pressure or current waves may be generated, depending upon the arrangement of the armature winding, pole-

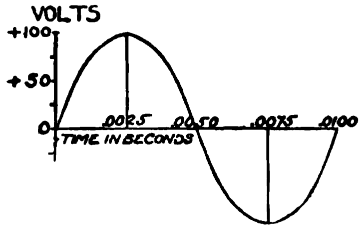
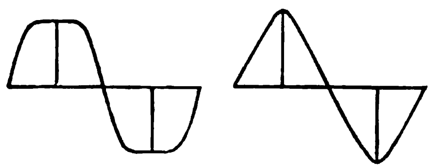


Fig 77. Representation of Alternating E.M.F.



Figs. 78 and 79. Flat-topped and Peaked Wave Forms.

pieces, etc. It is possible, by having the pole-faces either considerably wider or considerably narrower than the armature coils to produce a *flat-topped wave* (Fig. 78); or by making the coils exactly the same width as the pole-pieces, a *peaked wave* (Fig. 79) may be obtained. If the lines of force are excessive at the edges of the poles, extra waves, or *upper harmonics J B W*, are superimposed upon the main or *fundamental* wave *A C* (Fig. 80). The extra

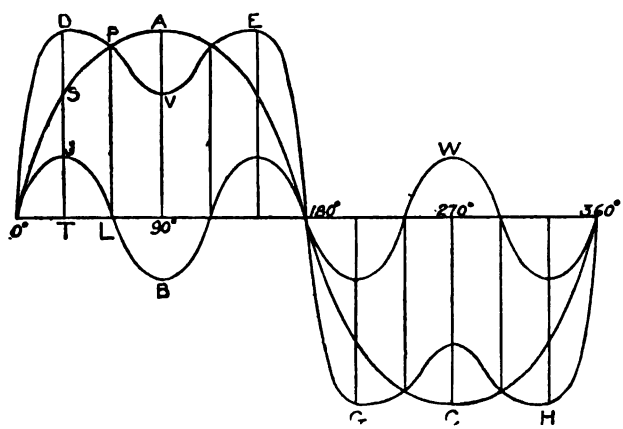


Fig. 80. Alternating E.M.F. with Third Harmonic.

wave, *J B W*, shown is the third harmonic, being always an odd number; but in some cases the fifth, seventh, or almost any odd harmonic may be present. These harmonics are alternating pressure or current waves of three, five, seven, etc., times the frequency of the fundamental wave *A C*, which are generated simultaneously

with the latter, and modify its form. In the case represented, *D V E G H* is the wave of *E.M.F.* that is actually produced, being the combination of the fundamental *A C* and the third harmonic, *J B W*. For example, the voltage at *D* is the sum of *S T* and *J T*. At *V* it is the algebraic sum of *A* and *B*, and so on. The ideal

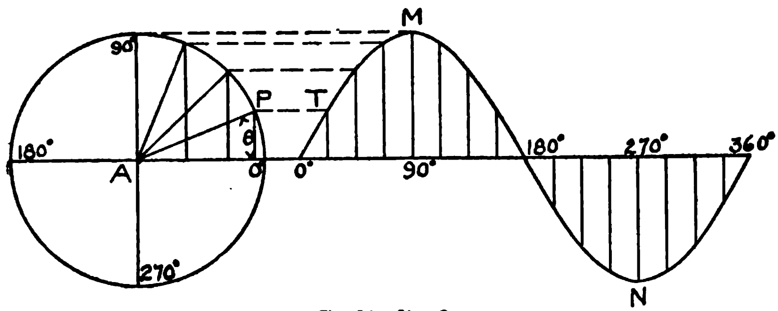


Fig. 81. Sine Curve.

form of wave generated by a coil of wire revolving about an axis in a uniform field is the *sine-curve*, in which the *E.M.F.* at any point, *P*, is proportional to the sine of the angle θ, through which the coil has moved (Fig. 81).

If the maximum value of the *E.M.F.* at *M* is E_{max}, then the instantaneous value e at any point is

$$e = E_{max} \sin \theta. \tag{32}$$

When the current wave is also a sine-curve, a similar expression gives the instantaneous value as follows:

$$i = I_{max} \sin \theta. \tag{33}$$

The sine-wave being the ideal form, practically all calculations are based upon it; other forms tend to be converted into the sine curve; and it seems to be the best for general use, so it should be accepted for the same reason that standard weights and measures, screw-threads, etc., are adopted. This is true, even though some other form might have advantages for certain purposes. The question has been much discussed;* but the tendency has been for manufacturers generally to adopt the sine-form, the actual waves of pressure and current in most commercial apparatus being close approximations to the true sine-curve.

If all alternating current apparatus is designed for the sine-wave

* *Electrical World*, Aug. 4, 1894, p. 107, and many other issues to Dec. 1, 1894.

it is possible to operate dynamos, motors, measuring instruments, etc., on any circuit, thus avoiding the endless confusion and difficulties that would arise if a different form of wave were adopted by each manufacturer and for each particular purpose.

Effective Values of Alternating Pressures and Currents. — Since the value of an alternating current is continually varying, it is usually more convenient to consider its *mean value;* but this *is not the ordinary arithmetical average.* If an alternating current is flowing through a conductor, its heating effect at any instant will be proportional to the square of the current strength; and the average heating effect for the whole time during which it flows will be the average of these squares, — that is, the mean square. It follows, therefore, that a direct current, to produce the same heating effect, would have a value equal to the square root of this quantity, that is, $\sqrt{\text{mean square}}$. The same is true of alternating current *E.M.F.*, since the heating effect is $\frac{E^2}{R}$; so that, with a constant resistance, the heating is proportional to the square of the voltage. The square root of the mean square of the voltage or current is called its *effective* value, and is the quantity which is indicated by alternating current volt- or ampere-meters. For a sine-wave the effective pressure or current is $\frac{1}{\sqrt{2}} = .707$, or about 71 per cent of the maximum value, and conversely, the maximum is $\sqrt{2} = 1.41$ times the effective value, or 41 per cent greater. These relations may be summed up as follows:

$$E_{effec} = \sqrt{\text{mean square of } e} = \frac{E_{max}}{\sqrt{2}} = .707\ E_{max}; \qquad (34)$$

$$I_{effec} = \sqrt{\text{mean square of } i} = \frac{I_{max}}{\sqrt{2}} = .707\ I_{max}. \qquad (35)$$

In practical cases it is usually sufficient to determine the effective volts and amperes of alternating currents, the instantaneous values being rarely considered except for the purpose of deducing formulas, studying phenomena, and other investigations. The term *virtual* is sometimes applied to the $\sqrt{\text{mean}^2}$ values instead of the word effective; but the latter word is now generally adopted.

Inductance is one of the three fundamental quantities which affect the flow of an alternating or other varying current, the other two being resistance and capacity. It is due to inductive action

of the circuit on itself, or of one portion of the circuit on another portion of the same circuit, in which cases it is called *self-induction;* or it may be due to the action of one circuit upon another independent circuit, in which case it is called ***mutual induction.*** The former is the one generally considered in transmission, and will be treated first.

The unit of inductance, or the "coefficient of self- or mutual induction," is called the *henry*, which is the inductance of a circuit when the *E.M.F.* induced in it is one volt, while the inducing current varies at the rate of one ampere per second. For example, if a counter *E.M.F.* of one volt is set up in a coil when the current is increased at the rate of one ampere per second, then the self-inductance of that coil is one henry.

The physical cause of the phenomenon of self-induction is the fact that a current flowing in a conductor tends to produce magnetic lines of force around itself. If the conductor is a helix of wire, the lines produced by each turn pass through that turn and through most of the others, so that the total flux through the helix is large. When the current varies, the lines of force also vary in number, and necessarily cut the turns of wire, thereby setting up an *E.M.F.* in the latter. With increasing current this *E.M.F.* is counter, and opposes the flow; with decreasing current it aids it; but when the current is steady no *E.M.F.* is induced, since the lines of force do not vary or cut the conductor. In the case of mutual induction, it is evident that a second coil B in the neighborhood will be cut by the lines of force produced by the first, tending to set up an *E.M.F.* in B, which will cause a current to flow in it, or will oppose or aid a current already flowing, according to the relative directions of the lines of force and the current.

Inductance was defined by the Chicago Electrical Congress of 1893 in terms of the *E.M.F.* generated, but it is also proportional to the number of turns of wire and to the average flux through each when unit current is flowing. This is similar to the first definition, since the production of a certain number of lines of force by one ampere in one second tends to generate a certain *E.M.F.*

A third definition of inductance may be based upon the electromagnetic energy stored in a coil when a unit current is flowing, which energy is proportional to the square of the flux density, other things being equal.

These three definitions may be summed up as follows:

Three Definitions of Inductance. — Calling L the inductance in henrys, e and i the instantaneous values of the *E.M.F.* in volts and the current in amperes respectively, n the instantaneous value of the average flux through each turn of wire, Z the number of turns, W the energy in joules and $\frac{di}{dt}$ the time rate of variation of the current, we have:

in terms of *E.M.F.*

$$e = L\frac{di}{dt} \tag{36}$$

in terms of lines of force and turns of wire

$$\frac{10^8}{nZ} = Li \tag{37}$$

in terms of energy

$$W = \tfrac{1}{2} Li^2. \tag{38}$$

Reactance due to Self-Induction. — It has been shown that the effect of inductance in an alternating current circuit is to oppose the flow of current on account of the counter *E.M.F.* which it sets up. This opposition may be considered as an *apparent resistance*, and is called *reactance* to distinguish it from true ohmic resistance. The value of the reactance due to inductance is given by the following expression, in which f is the frequency in periods per second, and L is the inductance measured in henrys

$$\text{Reactance} = 2\pi fL. \tag{39}$$

The result obtained gives the equivalent or apparent resistance in ohms.

Example. — A coil of wire having a self-inductance of 25 millihenrys = .025 henry is supplied with an alternating current at a frequency of 100 periods per second. Its reactance, assuming its ohmic resistance to be negligible, would be

$$2\pi fL = 2 \times 3.1416 \times 100 \times .025 = 15.7 \text{ ohms.}$$

Such a coil would have the same apparent resistance as a non-inductive circuit of 15.7 true ohms, and if connected to an alternating current source giving 1000 volts at 100 frequency, the effective current flowing through the coil would be $\frac{1000}{15.7} = 63.7$ amperes.

Impedance due to Resistance and Inductance. — Actual circuits always have resistance as well as inductance, and in most cases the former cannot be neglected. The combined effect of resistance

and inductance is called *impedance* to distinguish it from the other two, and has the following value in ohms (apparent resistance).

$$\text{Impedance} = \sqrt{R^2 + (2\,\pi f L)^2}. \tag{40}$$

Example. — A coil of wire has a resistance of 20 ohms and an inductance of .025 henry. For an alternating current having a frequency of 100 the impedance of the coil is

$$\sqrt{R^2 + (2\,\pi f L)^2} = \sqrt{20^2 + 15.7^2} = 25.4 \text{ ohms.}$$

Supplied with 1000 volts the coil would receive a current $\frac{1000}{25.4} = 39.3$ amperes.

The relations expressed analytically in (40) are evidently represented graphically by the right-angle triangle in Fig. 82. The resistance R in ohms is laid off on a convenient scale to form the base, the reactance $2\,\pi f L$ is laid off also in ohms to form the perpendicular, and the impedance in ohms is found by measuring the hypothenuse of the triangle, since it is equal to the square root of the sum of the squares of the other two.

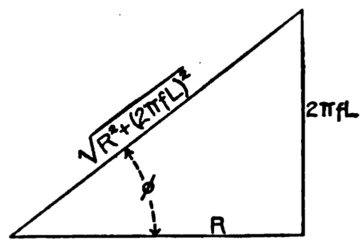


Fig. 82. Graphical Representation.

Lag of Current due to Inductance. — Besides opposition or reactance to an alternating current, inductance also causes the latter to lag behind the *E.M.F.* which produces it. The curve *EF* in Fig. 83 represents the waves of an alternating *E.M.F.* impressed upon a circuit containing ohmic resistance without inductance or capacity. In such a case the resulting current will reach its maximum as well as zero values at the same instants as the *E.M.F.*, and may be represented by the curve *CD.* If now a self-induction coil be introduced into the circuit in series with the resistance, the current waves will lag with respect to those of *E.M.F.*; that is, the maximum current will flow a little later than the instant of maximum *E.M.F.*, as indicated by the dotted curve *GH.* The amount of this lag is measured as an angle called the *angle of lag*, assuming one complete period to correspond to 360°. In Fig. 83 the current wave is shown as having its zero value one-eighth of a period, or 45° behind the zero *E.M.F.*, and the same for the maximum and other corresponding points, hence the angle of lag is 45°.

The tangent of the angle of lag with a given resistance R and inductance L in the circuit is

$$\tan \phi = \frac{\text{reactance}}{\text{resistance}} = \frac{2\pi f L}{R}. \qquad (40a)$$

Referring to Fig. 82, it is evident that the tangent of the angle ϕ is equal to $2\pi f L \div R$; therefore ϕ represents the angle of lag, which may be easily determined graphically in this way. It is apparent, from Fig. 82, that the angle of lag ϕ is small if the resistance is

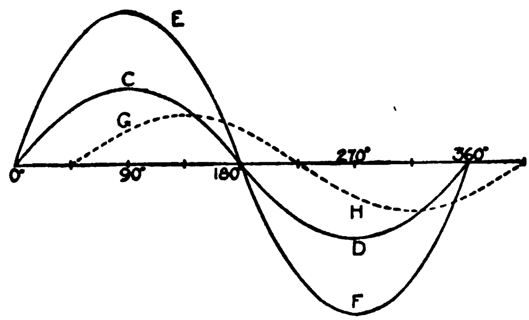


Fig. 83. Lag of Alternating Current.

large compared with the inductance L, unless the frequency is high. It is a fact also, that however large the inductance or frequency, and however small the resistance, the angle of lag can never be greater than a right angle, or 90°. This is evident in (40a), since $\phi = 90°$ when its tangent is infinity.

Example.—A circuit has a resistance of 2 ohms and an inductance of .0016 henry. What is the angle of lag for an alternating current having a frequency of 100?

$$2\pi f L = 2 \times 3.1416 \times 100 \times .0016 = 2 \text{ ohms}.$$

The resistance R is also 2 ohms, therefore $\tan \phi = \frac{2}{2} = 1$ and ϕ is 45°. This is the condition shown in Fig. 83, the current wave GH (dotted) being 45° behind the $E.M.F.$ wave EF. The curve CD represents the current that would flow if a wire of 2 ohms resistance without inductance were supplied with 100 volts alternating $E.M.F.$, the current at any instant having one half the numerical value of the $E.M.F.$ its effective value being $100 \div 2 = 50$ amperes with no lag. The addition of .0016 henry inductance produces a reactance of 2 ohms, which combined with the resistance of 1 ohms, makes an impedance of $\sqrt{2^2 + 2^2} = 2.82$ ohms, which is much less than their arithmetical sum.

The current is $100 \div 2.82 = 35.5$ amperes, so that the effect of inductance is to diminish the current, and cause it to lag as shown by comparing curves CD and GH in Fig. 83.

Determination of the Power of an Alternating Current. — In a circuit containing ohmic resistance only, the current wave C does not lag with respect to the *E.M.F.* wave E, and the power is represented by the curve PQ in Fig. 84. At any instant the power in watts is the product of the *E.M.F.* and current at that instant, but for convenience these values (curve PQ) are plotted on a smaller scale than E and C. The power is positive at all times, since the product of the positive values of E and C as well as the negative values of D and E are always positive, and its effective value is the $\sqrt{\text{mean}^2}$ of these products, which is simply the product of the effective *E.M.F.*, and current, as read on a volt and an ampere-meter, that is

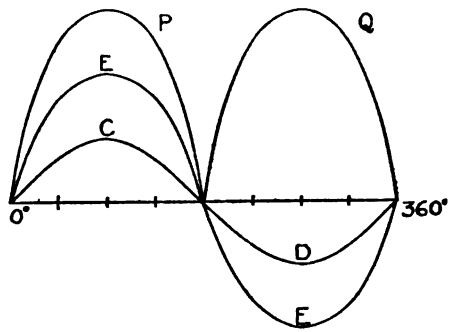


Fig. 84. Power of Alternating Current with no Lag.

$$\text{Power} = E \times I. \tag{41}$$

With inductance in the circuit, the current lags behind the *E.M.F.* and the power may be represented by the curve $PRQS$ in Fig. 85. The negative values R and S of the power are due to the fact that the current C is positive when the *E.M.F.* is negative, or *vice versa*; hence the actual power is reduced, being the algebraic sum of these quantities. When the reactance is very great compared with the resistance, the current lags 90°; and the negative power at T and U, in Fig. 86, is equal to the positive power at P and Q, so that the actual power is zero. All that occurs is a charging and discharging of electro-magnetic energy in the coil, the amount returned being nearly equal to that stored. It should be noted that the frequency of the power curves in Figs. 85 and 86 is twice that

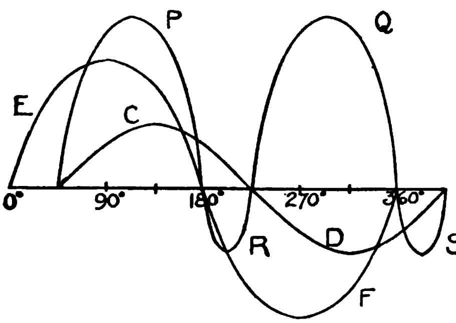


Fig. 85. Power of Alternating Current with 45° Lag.

of the *E.M.F.* or current. The effective power, when the *E.M.F.* and current differ in *phase* — that is, one lags behind the other — is

$$\text{Power} = EI \cos \phi. \quad (42)$$

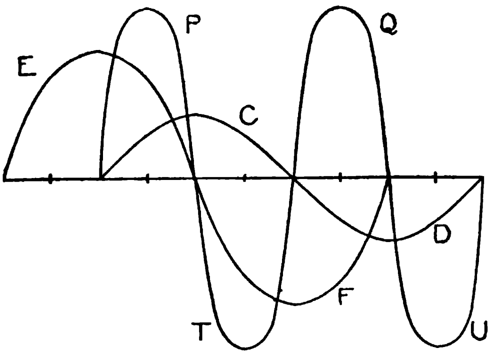


Fig. 86. Power of Alternating Current with 90° Lag.

In this expression $\cos \phi$ is the cosine of the angle of lag, and is called the *power factor*, since it is the ratio of the *real power* to the *apparent power EI*.

To measure alternating current power, it is necessary to know the angle of lag if separate volt- and ampere-meters are used, or to employ a watt-meter, which gives the true reading directly.

Example. — Taking the same case as before in which the *E.M.F.* is 100 volts, the current is 35.5 amperes and the angle of lag is 45°, the real power would be $100 \times 35.5 \times \cos 45° = 100 \times 35.5 \times .71 = 2520$ watts, while the apparent power is $100 \times 35.5 = 3550$ watts.

Capacity is the third quantity which effects the flow of an alternating or other variable current. This physical quantity is familiar in the case of the electrostatic capacity of a Leyden jar or a condenser, and is measured in terms of the *farad* as a unit, being the capacity of a condenser which will contain one coulomb of charge at a potential of one volt. Since this unit is much too large for ordinary use, the *microfarad*, or millionth of a farad, is generally employed.

Reactance due to Capacity. — When the two terminals *D* and *G* of a condenser are connected respectively to the two wires *BD* of an alternating current source *A*, as indicated in Fig. 87, the condenser will be charged and discharged continually, so that current will flow in the wires *B* and *D* in spite of the fact that the two sides *D* and *G* of the condenser are insulated from each other, which prevents the actual passage of current through it. Thus we see that a condenser is equivalent to a closed circuit

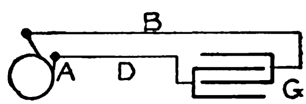


Fig. 87. Condenser in Alternating Current Circuit.

having a certain resistance, or, in other words, it has an apparent resistance in ohms which is called its reactance, corresponding to that due to inductance. Evidently the flow of current increases directly with the capacity and with the frequency, therefore the reactance is inversely proportional to these quantities. Calling K the capacity in farads, the reactance in ohms is:

$$\text{reactance} = \frac{1}{2\,\pi f K}; \tag{43}$$

$$\text{current} = E \times 2\,\pi f K. \tag{44}$$

Example.—What is the reactance of a 50-microfarad condenser to an alternating current of 100 frequency? The reactance from (43) is:

$$\frac{1}{2\,\pi f K} = \frac{1}{2 \times 3.1416 \times 100 \times .000050} = \frac{1}{.031416} = 31.8 \text{ ohms.}$$

If the *E.M.F.* of the supply is 100 volts, a current of $\frac{100}{31.8} = 3.14$ amperes would flow in the connecting wires.

Lead of Current due to Capacity.—A condenser is supplied with an alternating *E.M.F.* represented by the curve *EFGH* in Fig. 88. It is evident that current will flow into the condenser in one direction while the *E.M.F.* varies from its greatest negative value E to its highest positive value F, and its direction is the same as that of the positive *E.M.F.*, therefore, a positive wave of current C is produced during that time. The condenser is fully charged when the *E.M.F.* reaches its maximum value F, so the flow into the condenser ceases and the current is zero. The *E.M.F.* then falls as shown by the line *FGH*, and the condenser discharges, producing the negative current wave D and so on. By comparing the two curves, it appears that the maximum current into the condenser occurs at a point C, which is 90° *ahead* of the maximum *E.M.F.* at F, and the same for other corresponding points. Hence, the charging current of a condenser has a *lead* with respect to the impressed *E.M.F.* The tangent of the angle of lead or negative lag is given by an expression analogous to (40a).

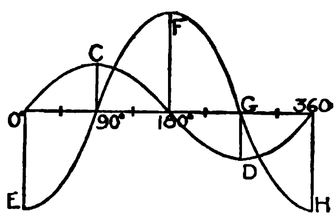


Fig. 88. Lead of Alternating Current.

$$\tan\phi = -\frac{\text{Reactance}}{\text{Resistance}} = -\frac{\frac{1}{2\,\pi f K}}{R}. \tag{45}$$

This angle may be determined graphically by a triangle, as indicated in Fig. 89, similar to Fig. 82; but in this case the reactance $\frac{1}{2\pi f K}$ is laid off downward, since it produces a lead instead of a lag.

Impedance due to Resistance, Inductance, and Capacity. — When a certain ohmic resistance is in series with a condenser, the impedance or combined apparent resistance in ohms is given by an expression corresponding to (40).

$$\text{Impedance} = \sqrt{R^2 + \left(\frac{1}{2\pi f K}\right)^2} \tag{46}$$

The same result is obtained graphically in Fig. 89. When inductance and capacity are both present in a circuit, the reactance of one tends to balance that of the other, so that the combined reactance is the algebraic sum of the two, that is:

$$\text{Reactance} = 2\pi f L - \frac{1}{2\pi f K} \tag{47}$$

When all three quantities — resistance, inductance, and capacity — are present in a circuit, the combined impedance is

$$\text{Impedance} = \sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f K}\right)^2} \tag{48}$$

$$\text{Tangent of angle of lag or lead} = \frac{2\pi f L - \frac{1}{2\pi f K}}{R}. \tag{49}$$

The graphical solution is shown in Fig. 90; the inductance reactance being laid off upward, and the capacity reactance down-

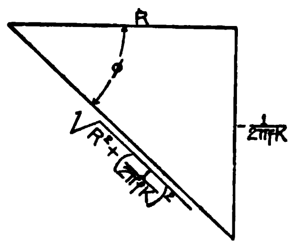


Fig. 89. Impedance and Lead Shown Graphically.

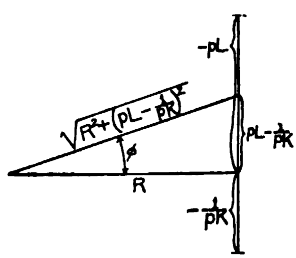


Fig. 90. Impedance and Lag due to Three Quantities.

ward, the difference being the perpendicular of the triangle of which the hypothenuse is the impedance and the angle ϕ is the lag or lead, as the case may be. For convenience, the constant $2\pi f$ is designated as p.

Example. — A circuit consists of a coil having 20 ohms resistance and .025 henry inductance in series with a condenser of 50 microfarad. What is the combined impedance and angle of lag when supplied with alternating current at a frequency of 100? The impedance from (48) is $\sqrt{20^2 + (15.7 - 31.8)^2} =$ 25.6 ohms, which is less than the capacity reactance (31.8 ohms) alone. The tangent of the angle of lead (the capacity reactance being greater than the inductance reactance) is

$$\frac{15.7 - 31.8}{20} = -\frac{16.1}{20} = -.805.$$

Power Factor with Resistance, Inductance, and Capacity. — It has already been stated (42) that Power $= EI \cos \phi$, when the current lags on account of inductance. It applies also to a leading current in a capacity circuit, and to a circuit containing resistance, inductance, and capacity. All that is necessary is to determine the angle of lag or lead from (49), or Fig. 90, and the cosine of that angle is the power factor. It is evident that the angle of lag, ϕ, is small when the induction and capacity reactances are nearly equal, so that they practically neutralize each other, in which case cos ϕ, the power factor, is almost 100 per cent

Resonance. — If $2\pi f L = \dfrac{1}{2\pi f K}$ in (48), then

$$LK = \frac{1}{(2\pi f)^2}. \qquad (50)$$

and the impedance of the circuit reduces to R simply, just as if neither inductance nor capacity was present. In other words, the two reactances exactly neutralize each other. The electrostatic energy in the condenser discharges when the electromagnetic energy in the inductance is being stored up, and *vice versa*. This condition is called electrical *resonance;* and the circuit is said to be *tuned* for the particular frequency indicated in (50), since with a given *E.M.F.*, the current will be much stronger for that frequency than for any other, the impedance being a minimum and equal to the resistance only. The induction- or capacity-reactance may each be very high, in which case the difference of potential across either pair of terminals will be much greater than the impressed *E.M.F.*, since the drop in voltage for each part of the circuit is equal to its reactance multiplied by the current. This can best be made clear by an example.

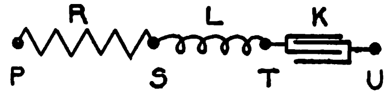


Fig. 91. Reactances in Series.

Example. — In Fig. 91 a non-inductive resistance R of 2 ohms is connected in series with a coil L, having .051 henry inductance (with insignificant resistance), and with a condenser, K, of 50 microfarads. What are the conditions when 100 volts alternating *E.M.F.* at 100 frequency is applied to the terminals P and U? The impedance from (48) is $\sqrt{2^2 + (32. - 31.8)^2} = \sqrt{4 + .04} = 2.01$ ohms. This is only .01 ohm, or one-half of one per cent more than the resistance alone. With 100 volts the current is $100 \div 2.01 = 49.8$ amperes. Since the reactance of the coil L is 32 ohms, the potential difference across its terminals S and T is $32 \times 49.8 = 1593.6$ volts, and between the terminals T and U of the condenser K it is $31.8 \times 49.8 = 1583.6$ volts. Each of these is nearly sixteen times as great as the impressed voltage at P and U, which is only 100. This multiplication of pressure when resonance happens to occur is sometimes the cause of breakdown in the insulation of conductors and apparatus.

Resonance may be set up by the frequency of the fundamental wave or by that of any upper harmonics (Fig. 80). With the fundamental frequency and with the third and fifth harmonics present as is often the case, there would be three values of the frequency f in (50), any one of which might satisfy the equation and give resonance, if the product $L\,K$ happened to have a corresponding value.

Circuits Containing Reactances in Series. — Equation (48), or the graphical methods shown in Figs. 82, 89, and 90, may be used to find the impedance of any combination of resistances, inductances, or capacities in series. In such a case, the sum of all the resistances should be substituted for R, the sum of all the inductances for L, and the sum of all the capacities for K in (48). These total values may be used also in the diagram represented in Fig. 90. The *E.M.F.* is then divided by the total impedance thus found in order to obtain the current. The potential difference between any two points of the circuit is the product of this current and the impedance between those points. The angle of lag is found by (49) using total values for R, L, and K. If one or two of these quantities are not present in any case, they disappear from the equations or graphical representations without affecting those quantities remaining.

Reactance E.M.F. — In Fig. 92 the horizontal line OA is laid off in proportion to the resistance of a certain coil, and the vertical line OB is made proportional to its reactance $= pL$, in which $p = 2\pi f$. When the rectangle is completed, the diagonal OD represents the impedance $= \sqrt{R^2 + (pL)^2}$, being the same as the hypothenuse in Fig. 82. Assuming a current of one ampere in the coil, the voltage across its terminal is $I\sqrt{R^2 + (pl)^2}$, which is numerically equal to the impedance; hence the line OD in Fig. 92

may be taken to represent that voltage. Similarly the line *OA* gives the drop due to the ohmic resistance, and the line *OB* shows the voltage required to overcome the reactance. That is, the impressed *E.M.F.* *OD* is resolved into two components at right angles to each other, one of which, *IR*, overcomes the resistance, and the other, *pLI*, overcomes the reactance. The reactance is, in fact, an opposing *E.M.F.*, having an effective value, *OF*, equal but directly opposite to *pLI*, and lagging 90° behind the current, the phase of the latter being represented by the line *OA*.

These relations, which are very important, may be stated as follows: With a given current *I* the effect of resistance is equivalent to a counter *E.M.F.* equal to *IR*, and represented by the line *OG*. With the same current, the reactance is actually an opposing *E.M.F.* having an effective value equal to *pLI*, and indicated by

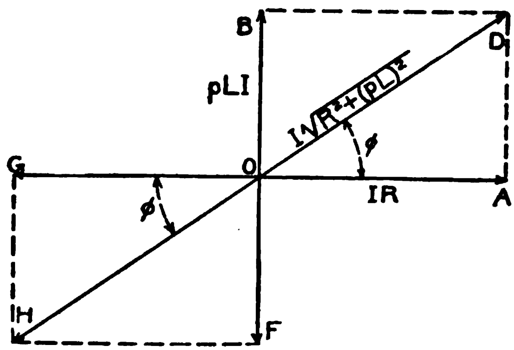


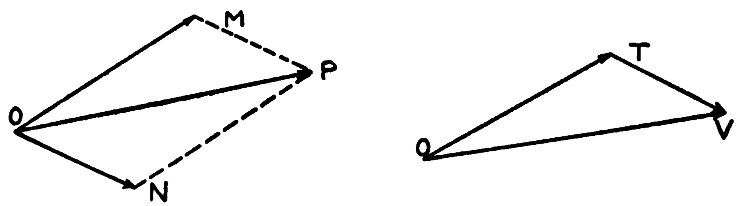
Fig. 92. Components of E.M.F.

OF. The combined effect of the two is equivalent to a counter *E.M.F.* equal to *OH*, which is their resultant. Hence *OD*, the impressed *E.M.F.*, must exactly balance *OH*; that is, it is equal and opposite as shown. The phase of the impressed *E.M.F.* is represented by the line *OD*, with respect to which the current phase *OA* has an angle of lag ϕ, and *OF*, the reactance *E.M.F.*, has a further lag of 90° behind the current.

Precisely similar diagrams and reasoning apply to the capacity reactance and angle of lead in Fig. 89 and to the combined inductance and capacity reactances in Fig. 90.

Composition and Resolution of E.M.F. and Current. — In the manner explained above, two or more alternating *E.M.F.*'s may be combined to form a resultant, or one *E.M.F.* may be resolved

into two or more components; and the same is true of alternating currents. For example, two alternators are running in series, the value and phase of the *E.M.F.* of one being represented by *OM* in Fig. 93, and the value and relative phase of the other's *E.M.F.* being represented by *ON*. The combined effect is the same as that of one *E.M.F.* having the value and phase *OP*, which is the resultant of the two. If *OM* and *ON* represent the phase and values of two alternating currents, the phase and amount of the resultant current are given by *OP*. This method applies to any



Figs. 93 and 94. Components and Resultants of E.M.F. and Current.

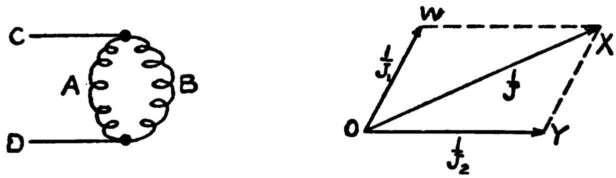
number of *E.M.F.*'s or currents having any phase angles, the various components being combined successively in pairs. Instead of constructing a complete parallelogram, it is sufficient to lay off *OT* to represent one *E.M.F.*, and *TV* to represent the phase and value of another *E.M.F.*, then *OV* is their joint phase and amount. In other words, their resultant is the vector sum *OV* of the two vectors *OT* and *TV*, representing their respective values and phases.

Impedance of Parallel Circuits. — With two or more simple resistances in parallel, the joint conductance is the sum of the several conductances; hence the joint resistance is the reciprocal of the sum of the reciprocals, that is:

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \cdots}. \qquad (51)$$

In the above, R is the joint resistance of the resistances r_1, r_2, etc., in parallel. If no inductance or capacity is present, this is true of alternating circuits, and always applies to steady direct currents. When there is inductance or capacity or both in one or more of several alternating circuits in parallel, it becomes necessary to consider the phases of the currents in the different branches.

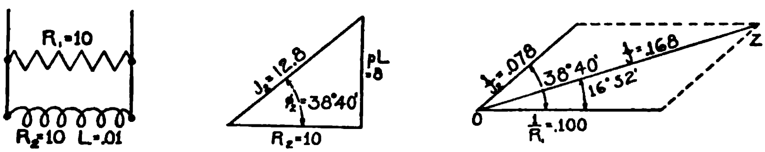
Two inductive coils A and B in parallel are assumed to be supplied with an alternating voltage by the conductors C and D in Fig. 95. To deduce a method for finding their joint impedance, let us suppose that OW in Fig. 96 represents the phase and value of the current in the coil A, and OY the phase and value of the current in B, then OX gives the phase and value of the resultant



Figs. 95 and 96. Impedance of Parallel Circuits.

current, which actually flows on the supply wires C and D. If the effective potential difference between C and D is one volt, and the impedance of the coil A is J_1, then its current OW is $\frac{1}{J_1}$, and if the impedance of B is J_2, its current OY is $\frac{1}{J_2}$. The resultant current OX must be $\frac{1}{J}$, in which J is the joint impedance of the two. The reciprocal of impedance is called *admittance;* therefore, *the joint admittance of two or more alternating circuits in parallel is the resultant of their several admittances.* The equivalent impedance is found by taking the reciprocal of the joint admittance. Many combinations of resistance, inductance, and capacity in series and in parallel are calculated out in the work on "Alternating Currents," by Professors D. C. and J. P. Jackson, pp. 151–220. The following examples are sufficient to show the method:

Examples.— A non-inductive resistance R_1 of 10 ohms is in parallel with an inductive resistance of 10 ohms and .01 henry as indicated in Fig. 97. What is the joint impedance and angle of lag for an alternating current having a fre-



Figs. 97, 98, and 99. Inductive and Non-inductive Circuits in Parallel.

quency of $127_\sim$? The impedance of the lower branch may be determined by constructing the triangle shown in Fig. 98, in which the base $= R_2 = 10$ and the perpendicular $= 2\pi fL = 800\,L = 8$. Hence, by calculation or by measurement

we find that the impedance, $J_2 = 12.8$ and the angle of lag $\phi_2 = 38°40'$. In another diagram (Fig. 99) the conductance $= \frac{1}{R^1} = .100$ is laid off horizontally to represent the upper branch, and the admittance $= \frac{1}{J_2} = .078$ is laid off at an angle $\phi_2 = 38°40'$ to represent the lower branch. Completing the parallelogram, it is found that the joint admittance $= \frac{1}{J} = .168$, so that the joint impedance $J = 5.95$ ohms, and the resultant angle of lag $\phi = 16°52'$.

In Fig. 100 a coil $R_1 = 10$ ohms, and $L = .01042$ henry is in parallel with a circuit containing a resistance $R_2 = 10$ ohms and a condenser having a capacity $K = 150$ microfarad, what is the joint impedance and angle of lag ϕ for an alternating current having a frequency of 127½? The impedance of the coil is found to be $J_1 = 13$ ohms, and the angle of lag $\phi_1 = 39°50^1$ in Fig. 101, and the impedance of the condenser circuit is $J_2 = 13$ ohms, and the angle of lead $\phi^2 =$

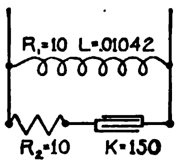


Fig. 100.

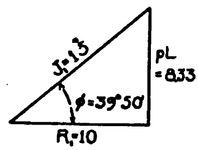


Fig. 101.

$= 39°50'$ in Fig. 102. The corresponding admittances, each of which is $1 \div 13 = .077$, are laid off in Fig. 103 with the same angles of lag and lead. The joint admittance $\frac{1}{J} = .117$, so that the joint impedance $J = 8.47$ ohms, and the resultant angle of lag $\phi = 0$, since the lag of one circuit balances the lead of the other. At 100 volts the main conductors F and G would supply $100 \div 8.47 = 11.7$ amperes. The power factor is 100 per cent ($\cos \phi = 1$) so that the true power would be $100 \times 11.7 = 1170$ watts. The current in each branch would be $100 \div 13 = 7.7$ amperes, one lagging $39°50'$, and the other leading $39°50'$, with

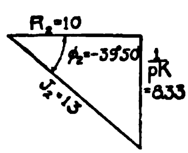


Fig. 102.

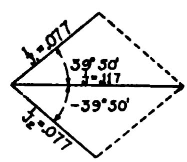


Fig 103.

respect to the impressed *E.M.F.* The fact that the actual current supplied (= 11.7 amperes) is not equal to the sum of those in the two branches ($2 \times 7.7 = 15.4$ amperes) shows that the discharging of one partly acts to charge the other, which is always the case when parallel circuits are not in the same phase.

Other combinations of resistance, inductance, and capacity may be treated in a similar manner.

Self-Inductance of Lines and Circuits. — It is possible to calculate the inductance of coils of wire, but difficult to do so, and in most cases it is determined by comparison with standard inductances. The inductance of aërial lines is easily calculated, since they are generally parallel, and the medium has a fixed permeability practically equal to one. Wires laid upon a wall of wood, or other non-conducting, non-magnetic substance, or otherwise placed out of proximity to such a substance, have practically the same inductance as aërial lines.

The following formulas may be used to determine the self-inductance of *two parallel aërial wires* forming part of the same circuit, and composed of *copper or other non-magnetic material.*

$$L \text{ per centimeter} = \left(.5 + 2 \log_e \frac{A}{r}\right) 10^{-9} \qquad (51)$$

In this expression L is the self-inductance in henrys per centimeter of each wire, A is the interaxial distance between the two wires, and r is the radius of each. The dimensions A and r may be expressed in terms of any unit, provided it is the same for both. Since the Napierian logarithms in the above equation are 2.302585 times the common logarithms, and as it is more convenient to use the diameter d of the wire instead of its radius, we have without appreciable error:

$$L \text{ per centimeter} = \left(.5 + 4.6 \log \frac{2A}{d}\right) 10^{-9} \qquad (52)$$

$$L \text{ per foot} = \left(15.24 + 140.3 \log \frac{2A}{d}\right) 10^{-9} \qquad (53)$$

$$L \text{ per mile} = \left(80.5 + 740. \log \frac{2A}{d}\right) 10^{-6} \qquad (54)$$

For each of two parallel *iron* wires we have the following expressions, in which the only change is the first constant:

$$L \text{ per centimeter} = \left(75 + 2 \log_e \frac{2A}{d}\right) 10^{-9} \qquad (55)$$

$$L \text{ per centimeter} = \left(75 + 4.6 \log \frac{2A}{d}\right) 10^{-9} \qquad (56)$$

$$L \text{ per foot} = \left(2286 + 140.3 \log \frac{2A}{d}\right) 10^{-9} \qquad (57)$$

$$L \text{ per mile} = \left(12070 + 740 \log \frac{2A}{d}\right) 10^{-6} \qquad (58)$$

In order to save the trouble of calculating the inductance with various sizes of and distances between wires, the following table is given:

INDUCTANCE, IN MILLIHENRYS PER MILE, FOR EACH OF TWO PARALLEL COPPER WIRES.

Interaxial Distance. Inches.	A.W.G. No. 0000 Diam. 0.460 inches.	000 0.4096	00 0.3648	0 0.3249	1 0.2893	2 0.2576	3 0.2294	4 0.2043
3	0.907	0.944	0.982	1.019	1.056	1.094	1.131	1.168
6	1.130	1.168	1.205	1.242	1.280	1.317	1.354	1.392
9	1.260	1.298	1.335	1.372	1.410	1.447	1.485	2.522
12	1.353	1.391	1.498	1.465	1.502	1.54	1.577	1.614
18	1.484	1.521	1.558	1.596	1.633	1.671	1.708	1.744
24	1.576	1.614	1.651	1.688	1.725	1.764	1.800	1.838
30	1.648	1.686	1.723	1.760	1.797	1.835	1.871	1.910
36	1.707	1.745	1.784	1 818	1.856	1.893	1.931	1.968
48	1.799	1.836	1.874	1.911	1.949	1.986	2.023	2.061
60	1 871	1.909	1.946	1.982	2.023	2 958	2.095	2.132
72	1.930	1.968	2.005	2.042	2.079	2.116	2.154	2.192
84	1.971	2.016	2.053	2.092	2.128	2.166	2.203	2.240
96	2.023	2.059	2.097	2.134	2.172	2.210	2.246	2.283

Interaxial Distance. Inches.	5 0.1819	6 0.1620	7 0.1443	8 0.1285	9 0.1144	10 0.1019	11 0.9074	12 0.08081
3	1.206	1.243	1.280	1.317	1.355	1.392	1.429	1.467
6	1.429	1.466	1.503	1.540	1.578	1.615	1.652	1.690
9	1.559	1.596	1.634	1.671	1.709	1.746	1.783	1 820
12	1.652	1.689	1.727	1.764	1.801	1 838	1.875	1 913
18	1.781	1.820	1.857	1.894	1.931	1.968	2.007	2.044
24	1.875	1.912	1.949	1.986	2.025	2.061	2.099	2.135
30	1.947	1.984	2.021	2.058	2.097	2.134	2.171	2 208
36	2.005	2.043	2.079	2.117	2.155	2.192	2.229	2.266
48	2.099	2.135	2 172	2.209	2.248	2.285	2.322	2.359
60	2.169	2.208	2.245	2.282	2.319	2.356	2.393	2.432
72	2.229	2.266	2.303	2.340	2.376	2.415	2.452	2.489
84	2.277	2.312	2.351	2.389	2.427	2.464	2.502	2.539
96	2.321	2.358	2.395	2.433	2.470	2.507	2.546	2.582

Examples.—To show the use of the above formulas and table, let it be required to determine the inductance of an overhead line, 1½ miles long, consisting of two No. 0000 copper wires, 48 inches apart. Since it is a metallic circuit with two conductors, the total inductance is due to 2 × 1½ = 3 miles of wire. From (54) the inductance per mile is

$$\left(L = 80.5 + 740 \log \frac{2A}{d} \right) 10^{-6}.$$

Substituting, in this expression, the value of the distance between the wires $A = 48$ inches, and the diameter of each wire, $d = .46$ inch, we have

$$L \text{ per mile} = \left(80.5 + 740.3 \log \frac{96}{.46}\right) 10^{-6} = .001799 \text{ henry.}$$

This is equal to 1.799 millihenry, and is the same value as that given in the first column of the table, and shows how those figures were obtained. The total inductance of the circuit is $3 \times 1.799 = 5.397$ millihenrys.

Impedance of Circuits. — Having obtained the inductance of a given line or circuit, by calculation or from the table, the reactance from (38) is $2\pi f L$, and the impedance from (39) is $\sqrt{R^2 + (2\pi f L)^2}$. The resistance R may be found in the table on page 8. Tables are often given showing the impedance of lines; but in order to cover the various frequencies, sizes of wire, and distance apart, they become too bulky to include in the present volume.

Mutual Inductance of Circuits. — The inductive effect of one circuit upon another separate circuit is called mutual inductance. The most familiar example in electrical engineering is to be found in the action between the primary and secondary coils of a transformer, and will be considered later under that head. If two conductors run parallel to each other, as, for example, two overhead lines upon the same poles, an alternating current in one tends to induce an alternating *E.M.F.* in the other, the direction of which is opposite to that of the inducing current. Consequently two parallel alternating currents which are exactly in phase tend to oppose each other; but if they differ by 180° in phase, that is, flow in opposite directions at the same time, they tend to aid each other. The currents in two or more parallel wires leading from the same terminal of an alternating current source would have about the same phase, assuming their angles of lag to be nearly equal, hence they tend to oppose each other. This opposition has the effect of increasing the drops in voltage similar to that due to self-induction; in fact, the action of these wires upon one another is practically the same as that of one element of a wire upon the other elements, but in the latter case it is called self-induction.

In practice, two alternating currents from independent generators would not be likely to remain exactly in phase, except for a few seconds at a time, so that their mutual induction upon each

other would produce opposing effects at one time, aiding effects at another, and so on as the phase changed. Supposing the frequency of one current to be 100 and of the other 100½ periods per second, the difference would be one period in two seconds, so that the voltage on each circuit would be raised once and lowered once every two seconds, causing very objectionable flickering in incandescent lamps. This is avoided by increasing the difference in frequency between the two currents. For example, if one were raised 5 per cent and the other lowered 5 per cent, the difference would be 10 periods per second, and the fluctuations in voltage occurring at that rate would be hardly noticeable. It is better, however, to have a still higher rate of 15 or 20 per second in order not to be perceptible or injurious to the eye. It is also possible to eliminate this effect by arranging or transposing the wires as described later.

Means of Reducing Self-Inductance. — In equations (51) to (58) it is evident that self-inductance is decreased by diminishing A the interaxial distance between two wires forming a metallic circuit. This somewhat paradoxical fact is understood when we consider that self-induction is proportional to the number of magnetic lines linked with a circuit, as defined on page 116. Consequently, the greater the distance between the two wires which constitute it, the more lines will be enclosed. Hence the wires should be as close together as possible in order to reduce self-inductance, the limit being the distance necessary for proper insulation, and in the case of overhead wires they must be sufficiently far apart not to swing too near each other.

If two insulated wires are laid side by side, or twisted together, their self-inductance becomes insignificant; and if *concentric* conductors are used, it disappears entirely, since the tendency to produce magnetic lines by one is neutralized by the other, the currents being equal and opposite. One wire, carrying an alternating current and running through an iron pipe, will have large self-inductance, on account of the great number of lines which are set up around it; but if both wires of a metallic circuit are put in the pipe, the self-inductance is very small.

Another way to reduce the drop due to self-induction is to *subdivide* the conductor, using several smaller wires having the same total sectional area.

Example. — An overhead line 1 mile long consists of two No. 0000 wires forming a metallic circuit, the distance between the wires being 24 inches. One mile of No. 0000 has .258 ohms resistance at 20° C., so the resistance of the circuit is $2 \times .258 = .516$ ohms. The self-inductance per mile from the table on page 130, is 1.576 millihenrys, or .003152 henrys for the circuit. At a frequency of 100 the impedance is $\sqrt{.516^2 + (628 \times .003152)^2} = 2.05$ ohms. With a current of 40 amperes the drop due to resistance is $40 \times .516 = 20.64$ volts, and the total drop is $40 \times 2.05 = 82$ volts. Using eight No. 6 wires in parallel the joint resistance would be .52 ohms, being almost exactly the same as before, or $.52 \times 8 = 4.16$ ohms for each wire. Assuming the distance apart to be the same, or 24 inches for each pair, and neglecting the mutual inductance between the pairs, the self-inductance from the table would be 1.912 millihenrys per mile, or .003824 for the circuit, and the impedance $\sqrt{.416^2 + (.628 \times .003824)^2} = 5$ ohms. The current in each wire is $40 \div 8 = 5$ amperes, so the resistance drop is $5 \times 4.16 = 20.8$ volts, and the total drop is $5 \times 5 = 25$ ohms. In this case the resistance drop is practically the same as before, and the impedance drop is only 25 volts, or about 20 per cent greater than the simple resistance drop, while in the previous case it was 82 volts, or four times the resistance drop.

The above example proves the great reduction in inductance drop effected by subdividing the conductor. This is sometimes said to be due to the use of *smaller* wires, but this is not true; in fact, the inductance itself is increased by reducing the size of wire, as shown in the foregoing example, and in equation (53). In reality, the impedance drop in the second case would probably be greater than that calculated, on account of the mutual inductance between the corresponding wires of each pair; but this need not be very great if they are not put close together, and may be practically neutralized by arranging or transposing the wires, as explained under the next heading.

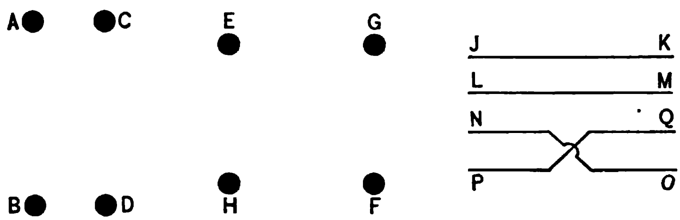
Another method of reducing the effect of inductance is to balance it by the effect of capacity. It was shown in connection with Fig. 90 and equations (46) and (49), that certain values of capacity in a circuit may completely or partially neutralize the reactance due to inductance.

In the Stanley electric power system condensers are used upon the circuit in connection with the motors to balance their inductance, so that the watless current is much reduced. In other words, the power-factor is raised, and the drop on the line is diminished. The amount of capacity, K, in farads, required to neutralize a certain inductance, L, in henrys, at a frequency, f, is obtained from (49) and has the following value:

$$K = \frac{1}{L\,(2\pi f)^2} \tag{58}$$

Synchronous alternating current motors may also be used to balance inductance, since they have the effect of capacity in causing the current to lead when their field magnets are over excited. By regulating the field excitation the power-factor can be raised to practically 100 per cent. The same effect is produced by rotary converters, and will be considered more fully later in connection with the polyphase transmission and direct-current distribution system.

Means of Reducing Mutual Inductance. — The simplest plan is to increase the distance between the conductors, as already stated; but this is limited by practical considerations, such as requirements for carrying the wires on the same pole. In such cases the effect of mutual induction would be great if the wires were arranged as



Figs. 104, 105, and 106. Arrangement of Conductors to Neutralize Induction.

represented in Fig. 104, in which *A* and *B* indicate the wires of one circuit, and *C* and *D* those of another parallel circuit. The wire *A* being very near the corresponding wire *C* of the other circuit, would tend to set up an opposing *E.M.F.* in it, and *C* would react upon *A* in a similar manner. The mutual induction of *B* and *D* would also have the same effect. If, however, the wires are placed equidistant, as shown in Fig. 105, any one conductor, *E*, will be acted upon equally by both wires, *G* and *H*, of the other circuit, since they are at the same distance from it. Consequently mutual induction between the two circuits is neutralized. This can also be accomplished by transposing the wires with respect to each other, at certain intervals, as shown in Fig. 106, in which the portion *N* of one wire, counteracts the effect of the part *Q* of the other wire of the same circuit. Consequently the inductive action upon the other circuit, *JK* and *LM*, is nil.

It should be noted, however, that the self-induction of either circuit is not materially altered by these arrangements, being dependent upon the average distance between the two wires of each circuit, and not upon the presence of the other circuit.

"**Skin Effect**" is the name given to the phenomenon according to which alternating currents tend to have a greater density near the surface than they have along the axis of a conductor. If we imagine a wire to be made up of elementary filaments parallel to its length, it is evident that the central or axial filament will be surrounded by a greater number of magnetic lines than an element at the surface, since each filament tends to set up lines around itself. This fact produces no effect upon a steady current after it has been established, there being no variation in the number or position of the lines. Hence a steady current has a perfectly uniform distribution throughout the entire cross-section of a conductor having a uniform specific resistance.

In the case of an alternating current, the additional lines of force that inclose the filaments near the axis are reversed twice during each period, the effect being to generate a greater back *E.M.F.* of self-induction than for the outer filaments of the wire. Consequently the current density is less near the axis than it is near the surface. With high frequency and large conductors this action may be so great that there is actually a *back* flow of current at or near the axis. But with ordinary sizes of wire and frequencies, the effect is small.

This "skin effect" is generally treated as an increased apparent resistance of a conductor, being called its *virtual resistance;* and since it involves a larger drop in voltage and a greater loss of energy, it is practically the same as true resistance.

In Fig. 107, which shows graphically the values of virtual resistance, R_a is the apparent or virtual resistance for a given alternating current, R_d is the true ohmic resistance of a copper conductor at 20° C. (68° F.), A is the area of cross-section of the latter in circular mils, and f is the frequency.

A conductor one inch in diameter has a cross-section of one million circular mils, so that at a frequency of 100, the product of A and f, is 100,000,000. Referring to Fig. 107, we find that $R_a \div R_d = 1.21$; that is, the virtual resistance is 21 per cent greater than the true resistance, consequently this is too large a

conductor to use at that frequency. On the other hand, No. 0 wire has a sectional area of 105,500 circular mils, and with the same frequency of 100, the product $A\ f = 10{,}550{,}000$, which would give a virtual resistance less than one-half of one per cent greater than the true value, and need not be considered practically. Frequencies higher than 135 are rarely used in practice, and with a conductor one-half inch in diameter $f\ A = 135 \times 250{,}000 = 33{,}750{,}000$, and $R_a \div R_d = 1.03$ approximately. The conclusion is that with conductors smaller than one-half inch diameter, the increased resistance due to "skin effect" is less than 3 per cent for commercial frequencies. If a larger cross-section than this is required it should be subdivided among several wires in parallel, or

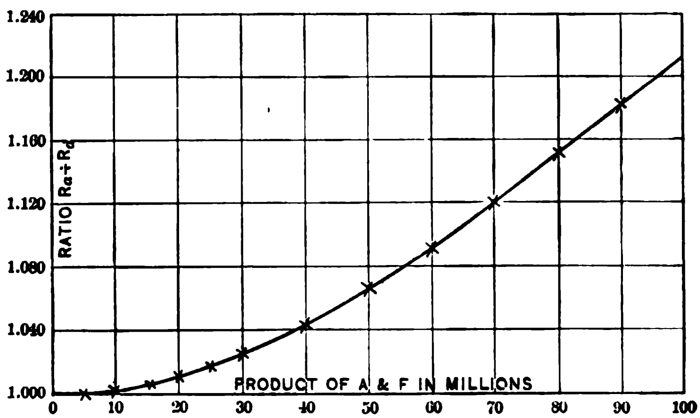


Fig. 107. Curve Showing Corrections for "Skin Effect."

the conductor may be made hollow or in the form of a flat bar, the "skin effect" being greatly reduced thereby. It has already been shown, on page 132, that the self-inductance drop is reduced by subdividing conductors, but the present phenomenon is a different one, and should be considered separately.

With iron conductors the virtual resistance is much greater than with copper or other non-magnetic metal; but iron is not often used to carry alternating currents, and the exact value of the permeability is not easily determined,* so that formulas will not be given.

Capacity of Overhead, Underground, and Submarine Conductors.—It is possible to predetermine the electrostatic capacity of elec-

* Merritt, *Physical Review*, November, 1899.

trical conductors, and almost all cases will come under one of the following heads:

Case 1. *Insulated conductor with metallic protection;* for example, an iron-armored submarine cable, or a lead-covered underground conductor, having the metallic sheathing connected with the earth, which is the usual condition.

Case 2. *Single aërial conductor with earth return.*

Case 3. *Metallic circuit consisting of two parallel aërial conductors.*

In the following expressions, K is the capacity in farads, k is the dielectric constant, D is the internal diameter of the metallic covering, d is the diameter of the conductor, h is the height above the ground of an aërial wire, and A is the interaxial distance between two parallel wires. In cases 2 and 3, the medium being air, $k = 1$, and does not appear in the equations. This assumes that the conductors are bare; but if they are covered with insulation of ordinary thickness it would only slightly increase the capacity, k being greater than 1 for insulating materials. The proximity of other conductors may increase the capacity considerably, but their effect is difficult to calculate.

Case 1. Insulated conductor with metallic covering.

$$K \text{ per centimeter} = \frac{241.5\ k\ 10^{-15}}{\log \frac{D}{d}} \tag{59}$$

$$K \text{ per foot} = \frac{7{,}361.\ k\ 10^{-15}}{\log \frac{D}{d}} \tag{60}$$

$$K \text{ per mile} = \frac{38.83\ k\ 10^{-9}}{\log \frac{D}{d}} \tag{61}$$

Case 2. Single aërial conductor with earth return.

$$K \text{ per centimeter} = \frac{241.5 \times 10^{-15}}{\log \frac{4h}{d}} \tag{62}$$

$$K \text{ per foot} = \frac{7{,}361. \times 10^{-15}}{\log \frac{4h}{d}} \tag{63}$$

$$K \text{ per mile} = \frac{38.83 \times 10^{-9}}{\log \frac{4h}{d}} \tag{64}$$

Case 3. Two parallel aërial conductors forming metallic circuit.

$$K \text{ per centimeter of each wire} = \frac{120.8 \times 10^{-15}}{\log \frac{2A}{d}} \quad (65)$$

$$K \text{ per foot of each wire} = \frac{3681. \times 10^{-15}}{\log \frac{2A}{d}} \quad (66)$$

$$K \text{ per mile of each wire} = \frac{19.42 \times 10^{-9}}{\log \frac{2A}{d}} \quad (67)$$

Examples. — What is the capacity of one mile of No. 0 (A. W. G.) lead-covered cable, with rubber insulation .15 inch thick? Substituting in (61) for d, the diameter of No. 0 wire = .325 inch, and for D the external diameter of the insulation = .325 + (2 × .15) = .625 inch, and for k the dielectric constant of pure rubber = 2.5, we have:

$$K \text{ per mile} = \frac{38.83\,k\;10^{-9}}{\log \frac{.625}{.325}} = 342. \times 10^{-9} \text{ farad} = .342 \text{ microfarads.}$$

What is the capacity of one mile of single overhead bare No. 0 wire, 10 feet above the ground, with earth return? Substituting in (64) the values of h and d, *both in inches*, we have:

$$K \text{ per mile} = \frac{38.83 \times 10^{-9}}{\log \frac{4 \times 120}{.325}} = 12.2 \times 10^{-9} \text{ farad} = .0122 \text{ microfarad.}$$

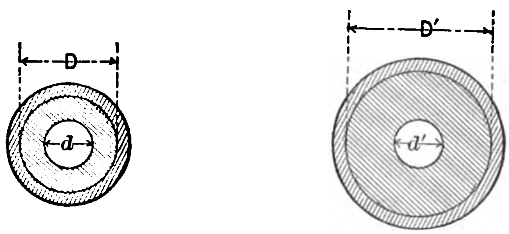
What is the capacity of two parallel overhead bare No. 0 wires, 12 inches apart, and each one mile long? Substituting in (67), we have:

$$K = \frac{2 \times 19.42 \times 10^{-9}}{\log \frac{2 \times 12}{.325}} = 20.8 \times 10^{-9} \text{ farad} = .0208 \text{ microfarad.}$$

Means of Reducing Capacity. — It is evident from equation (59) that the capacity of a given length of insulated conductor with metallic covering is decreased by diminishing k, the dielectric constant of the insulation, by increasing D, the internal diameter of the metallic covering, or by reducing d, the diameter of the conductor. Since the capacity varies in direct proportion to k, the insulating material should have the minimum dielectric constant. Unfortunately the best insulators usually have high values for k, notably india rubber, gutta-percha, paraffin, and mica. The dielectric constant of paper is comparatively low, and largely for that reason it is used for insulating the wires in a telephone cable. Paper is also used for the insulation of electric light and power

cables, and would have special advantages when it is desired to make the capacity as low as possible. This question will be considered further under the head of insulated and underground conductors.

The reduction of capacity by diminishing *d*, the diameter of the conductor, is limited in practice by the necessity for using a certain size in order to give sufficient current capacity, and not have too much resistance. It is also a fact that it is not practicable to materially reduce electrostatic capacity by augmenting *D*, or in other words, by increasing the thickness of the insulation. Fig. 108 represents a lead-covered cable, in which *d* is the diameter of



Figs. 108 and 109. Reducing Capacity by Increasing Thickness of Insulation.

the copper conductor, and *D* is the internal diameter of the lead covering. If the former is $\frac{1}{4}$ inch, and the latter $\frac{1}{2}$ inch, the thickness of insulation is $\frac{1}{8}$ inch. In Fig. 109 the thickness of insulation is twice as great, or $\frac{1}{4}$ inch; so that D' becomes $\frac{3}{4}$ inch, d' being $\frac{1}{4}$ inch the same as *d*. The capacity in the two cases will be in the ratio

$$\frac{1}{\log\frac{D}{d}} : \frac{1}{\log\frac{D'}{d'}} = \frac{1}{\log 2} : \frac{1}{\log 3} = 3.3 : 2.1$$

That is, the capacity is reduced only 36 per cent by doubling the thickness of insulation. The volume of insulation in the two cases would be in the proportion $(D^2 - d^2) : (D'^2 - d'^2) = 3 : 8$, which is an increase of 267 per cent, or almost three times as much. Since the amount of insulating material affects directly the cost and size of the cable, it would seldom pay to nearly treble this material in order to diminish the capacity to the extent of only 36 per cent. Hence in almost all cases the thickness of insulation is determined by its insulating qualities, and strength to withstand breakdown by electrical and mechanical pressures.

To reduce the capacity of overhead wires, the distance between them and from the ground should be increased. But even in this case the reduction is small compared with the increase in distance. Assume a horizontal wire $\frac{1}{8}$ inch in diameter, and one mile long, to be strung 30 feet above the earth, and another wire of the same size and length to be strung 60 feet above the earth. From (64) the capacities in the two cases will be respectively:

$$\frac{38.83 \times 10^{-9}}{\log 7200} = 10.1 \times 10^{-9} \text{ farad} = .0101 \text{ microfarad, and}$$

$$\frac{38.83 \times 10^{-9}}{\log 14400} = 9.3 \times 10^{-9} \text{ farad} = .0093 \text{ microfarad.}$$

The difference between the two values is only about 8 per cent, although one wire is twice as high as the other. The capacity with respect to each other of two parallel overhead wires 3 feet apart, each being $\frac{1}{8}$ inch in diameter and one mile long, is found from (67) to be

$$\frac{19.42 \times 10^{-9}}{\log 360} = 7.6 \times 10^{-9} \text{ farad} = .0076 \text{ microfarad.}$$

Increasing the distance between the wires to 6 feet, the capacity becomes

$$\frac{19.42 \times 10^{-9}}{\log 720} = 6.8 \times 10^{-9} \text{ farad} = .0068 \text{ microfarad.}$$

In this case the capacity is reduced $10\frac{1}{2}$ per cent by doubling the distance between the wires. From these examples it is evident that this way to diminish capacity is hardly economical where the cost of construction is greatly affected by the height and distance apart of wires, as is the case in pole lines. The method of balancing the reactance of capacity and inductance, already set forth on page 133, can be applied to reducing the effect of capacity in electrical circuits.

CHAPTER VIII.

PRINCIPLES OF ALTERNATING POLYPHASE CURRENTS.

THE advantages of two- and three-phase, or other polyphase systems, apply solely to the operation of motors. In fact, such currents are positively disadvantageous for supplying arc or incandescent lamps. Consequently this subject comes under the head of electric power rather than electric lighting. However, electric lamps are often used upon the same circuits with polyphase motors, and in many cases energy is transmitted over long distances by polyphase currents, to be converted into direct currents for local distribution to lamps; so it is necessary in the present volume to consider the principles of polyphase systems, and the methods of operating lamps upon them.

A two-phase current may be regarded as, and in most cases actually consists of, two *distinct* single-phase currents, flowing in

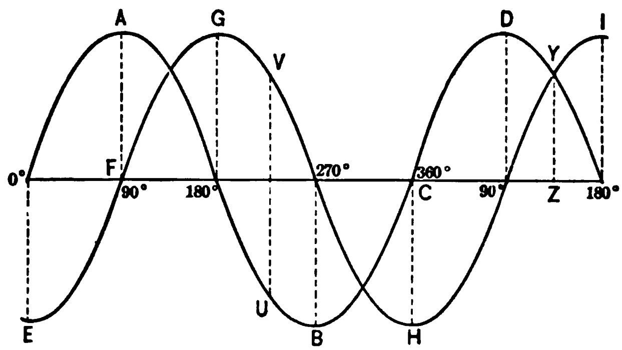


Fig. 110. Two-Phase Current.

separate circuits. There is often no electrical connection between them, their only relation being that of *time*. That is, they differ in *phase*. This condition is shown in Fig. 110, in which the curve *ABCD* represents one alternating current, and *EFGHI* represents

another, the difference in phase being 90°, the maximum value *G* of the second occurring 90° behind the maximum point *A* of the first, and so on for other corresponding points. If there is no lag of either current, the same curves can be taken to represent the two *E.M.F.*s, and with the same lag for both currents they would still be 90° apart in phase. If the lags were not equal, then the phase relation would be altered correspondingly. The two *E.M.F.*s or

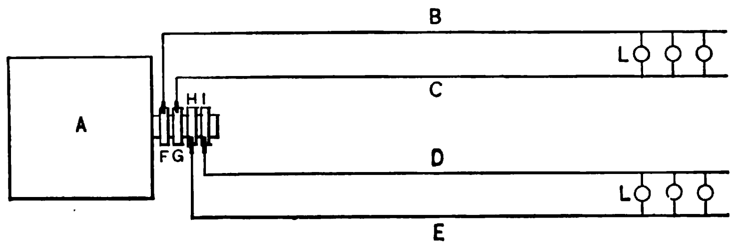


Fig. 111. Two-Phase, Four-Wire Circuit.

currents might have different maximum values, or different wave forms, but in practice they are usually made as nearly alike as possible. It is evident also that the difference in phase might be made anything between 0° and 360°; but it is almost always designed to be 90°, or one-quarter of a period, and for that reason is often called a *quarter-phase* current. Two-phase currents may be generated by two separate alternators, but in order to preserve the phase relation it would be necessary to have their shafts coupled or posi-

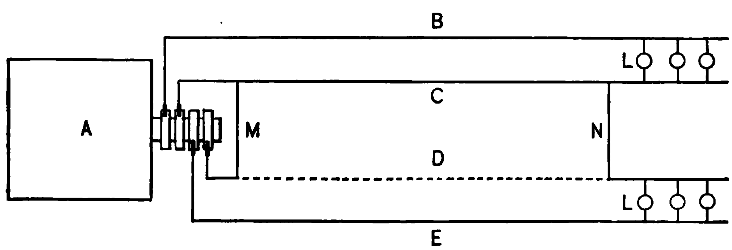


Fig. 112. Two-Phase, Three-Wire Circuit.

tively connected together. In practice, a two-phase current is usually generated by two separate windings upon one armature, the machine having the same general form as a single-phase alternator.

The two circuits may be kept entirely separate, as in Fig. 111, lamps *L* being connected to each, in which case four wires are required. In order to save one wire it is possible to use a common

return conductor for both circuits, as in Fig. 112, the dotted portion of one wire, *D*, being eliminated by connecting across to *C* at *M* and *N*. For long lines this is economical, but the interconnection of the circuits increases the chance of trouble from grounds or short circuits. It is also a fact that the current in the conductor *C* will be the resultant of the two currents, differing by 90° in phase. From the principle shown in Fig. 93, the value of this resultant is found in Fig. 113 to be $OR = \sqrt{2}\ OP = 1.41 \times OP$ the two-phase currents being represented by the components *OP* and *OQ* at right angles to each other. Consequently the resultant current in *C* is 1.41 times that flowing in either *B* or *E* in Fig. 112 and the cross-section of the wire *C* should be 41 per cent greater.

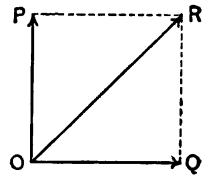


Fig. 113. Resultant of Two-Phase Currents.

A three-phase current consists of three alternating currents, differing in phase, as indicated in Fig. 114. One current is represented by the curve *JKL*, another by the curve *MNO*, and the third by the curve *PQR*, the maxima points *J*, *M*, and *Q* (or other corresponding points) being 120° apart in the ideal case, and ap-

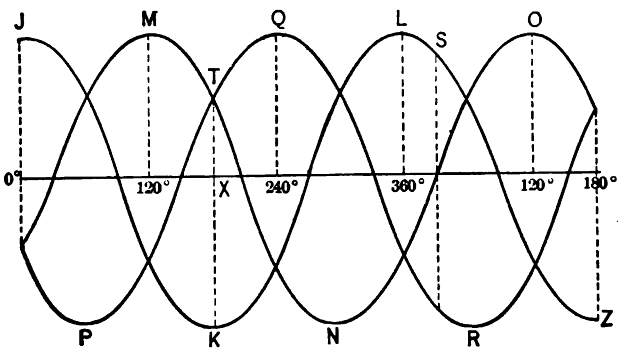


Fig. 114. Three-Phase Currents.

proximately so in practice. These three currents might be carried in three entirely separate circuits requiring six wires, being analogous to the two-phase, four-wire system in Fig. 111; or one common return conductor may be used, thereby saving two wires, and reducing the total number to four, as shown in Fig. 115. The armature windings and their phase relation are represented dia-

grammatically by the coils MA, MB, and MC, the three main conductors by AE, BG, and CF, the common conductor being indicated by the dotted line MN. The lamps L, L, L, are connected across between the common point N and the three main conductors.

If the three circuits are balanced (i. e., have equal currents) the common conductor MN will carry no current, and may be dispensed with. This is a most interesting and important feature of

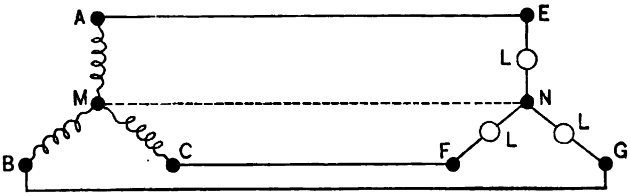


Fig. 115. Three-Phase Circuits with Y Connection.

the three-phase system. The simplest way to understand it is to consider that each wire acts as the return conductor for the other two. In other words, the algebraic sum of the three currents meeting at the common point N is equal to zero; consequently Kirchhoff's law is fulfilled. This fact is shown in Fig. 114, the algebraic sum of the ordinates of the three curves being equal to zero at any point. For example, at SR the ordinate of curve MNO is zero, and the ordinates of the other two are equal in value, but opposite in sign. At TK the sum of the two positive ordinates of the curves MN and PQ are equal to the negative ordinate of the other curve JKL, because $XT = \sin 30° = \frac{1}{2}$ and $XK = \sin 90° = 1$, and so on for other points. The same principle is proved in Fig. 116, in which a balanced three-phase

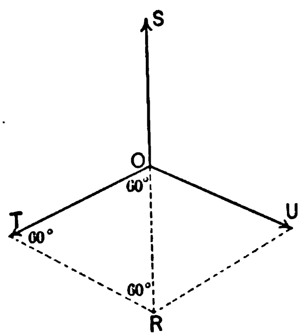


Fig. 116. Resultant Current, Three-Phase.

current is represented by three equal vectors at 120° with respect to each other. Two of these currents, OT and OU, are equivalent to their resultant OR, which is equal and opposite to the third current OS; consequently the resultant of all three currents is zero. In the operation of motors the three currents are usually equal, all three wires being connected to each machine, so that the fourth

wire *MN*, in Fig. 115, is superfluous; but for electric lighting this extra conductor is required, unless the lamps on the three circuits are balanced. If the currents in the three branches are not equal,

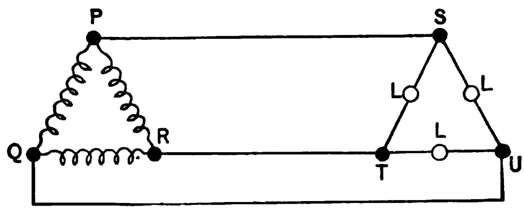


Fig. 117. Three-Phase Circuits with Δ Connection.

then the wire *MN* carries the difference between them, so that its function corresponds closely with that of the neutral conductor in the ordinary three-wire system described on page 70.

Another method of connecting three-phase circuits is shown in Fig. 117, and is called the Δ (delta) connection, the arrangement in Fig. 115 being designated as the Y connection. In either of these cases any lamp *L* is fed simply by the *E.M.F.* due to a single armature winding, *MA* in Fig. 115, or *QP* in Fig. 117. If, however, a lamp is connected across the outer terminals of the Y circuits, it receives a voltage which is the resultant of two *E.M.F.*s, that are in series, but differ by 120° in phase. This is shown in Fig. 118, *DA*, *DB*, and *DC* representing respectively the *E.M.F.*s of a three-phase armature winding with Y connection. Assuming the *E.M.F.* of each phase *DC* to be 100 volts, then the *E.M.F.* between *A* and *C* will be $\sqrt{3} = 1.73$ times as great, or 173 volts.

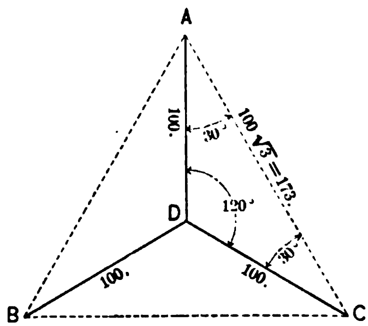


Fig. 118. Relative Voltage of Δ and Y Connections.

Production of Rotary Field by Two-Phase Current. — An iron ring, wound with insulated wire, as represented in Fig. 119, is supplied with two-phase currents at the four equidistant points *A*, *B*, *C*, and *D*, the two conductors of one phase being connected at *A* and *B*, and those of the other phase at *C* and *D*. Considering only one current, and assuming it to enter at *A*, the direction of winding is such that it will produce a south pole at *A*, and a north pole

at B, so that a compass needle placed inside the ring would tend to point vertically upward as indicated by the dotted arrow. This condition is represented at 1, in Fig. 120, the current $L\ M\ N$ having its maximum positive value, and the other current, $P\ Q\ R$, being zero at that instant. A moment later, the first current has decreased somewhat, and the other has increased, so that they are equal. In this case, each will tend to produce a south pole where it enters the ring, at A and D respectively, so that a resultant polarity is produced midway between, as shown at 2 by the arrow inclined at 45°. The next instant, at 90°, the current $L\ M$ has fallen to zero, and the current $P\ Q$ has reached its maximum, so that the arrow takes a horizontal position, as represented at 3. Again at 135°, the current $L\ M$ has reversed, tending to make a south pole at the bottom of the ring, and the needle will incline downward at an angle of 45°, as shown at 4.

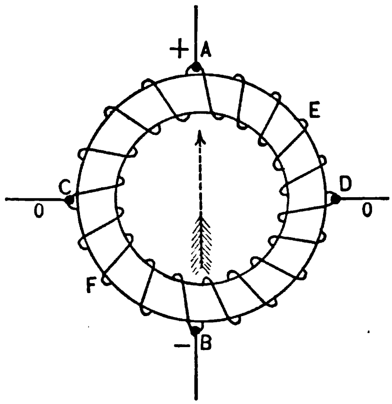


Fig. 119. Ring Supplied with Two-Phase Current.

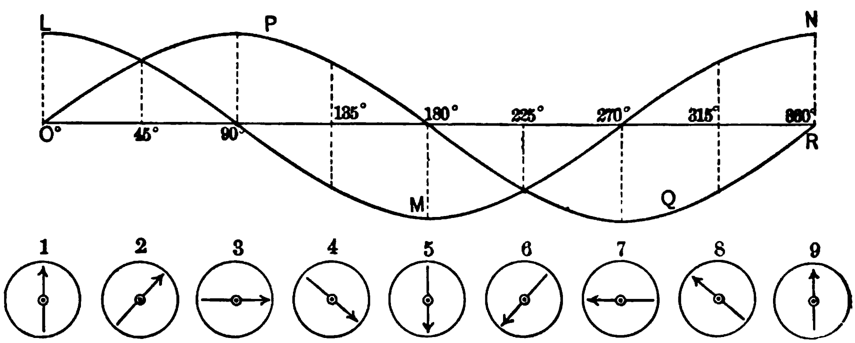


Fig. 120. Magnetic Resultants due to Two-Phase Current.

By following the successive conditions, the needle will be found to take the various positions represented at 5, 6, 7, 8, and finally at 9, it returns to its original vertical direction, the current having completed one period. Thus the needle tends to be carried around continuously by the shifting resultant field, so long as the ring is supplied with two-phase currents.

Principle of Polyphase Motors. — It is this capability of producing continuous rotation that gives the polyphase currents their interest and value, since it enables motors to be operated very successfully. The ring with the magnetic needle, in Fig. 119, illustrates the principle of the *synchronous* polyphase motor, since the armature revolves in exact synchronism with the phases of the currents. If the needle is replaced by a cylinder of laminated iron wound with conductors, like an ordinary armature, except that they are short-circuited, it is found that it will revolve also; but in this case the speed is a little less than that of a synchronous armature, the difference being called the *slip*, usually amounting to from 1 to 5 per cent. This slip represents a relative motion of the rotating field, with respect to the armature conductors; consequently the latter are cut by the lines of force, thereby inducing currents in them. It is the action of the field upon these induced currents which causes the armature to revolve, this type being called the *induction motor.* It is a remarkable fact that no current is supplied to the moving part, so that it need have no electrical connections made to it except for purposes of starting and regulation.

In some cases the construction is modified so that the part in which the currents are induced revolves, and the other part is stationary. For this reason, and because no energy is supplied directly to the so-called armature, it is considered more correct to distinguish the two elements of an induction motor as *rotor* and *stator*, or *primary* and *secondary*.

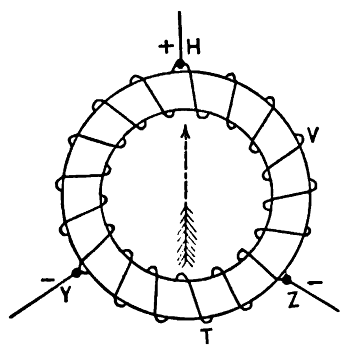


Fig. 121. Ring Supplied with Three-Phase Current.

The Action of Three-Phase Currents in producing a rotary field is quite similar to that described for two-phase currents. The ring in Fig. 121 is wound as before, but the current is led in at three equidistant points, H, Y, and Z, instead of at four points. Taking the instant when the current flowing in at H is a maximum, two currents flow out at Y and Z, each having one-half the value of the current entering at H. This tends to produce a south pole at H, and two north poles at Y and Z respectively. The resultant due to the latter is a south pole at

T, midway between *Y* and *Z*, consequently a magnetic needle would take the position shown by the dotted arrow. (This condition is represented at 0° in Fig. 114.) A moment later (at 60° in Fig. 114) currents enter at both *H* and *Z*, and a maximum current flows out at *Y*, hence the needle would point toward *V*. At the end of another one-sixth of a period (at 120° in Fig. 114), the maximum current will enter at *Z*, and the needle would turn to that point, and so on until it had made a complete revolution in one period of the alternating current.

Actual Forms of Polyphase Motors. — The synchronous type of polyphase motor is similar in principle and construction to the corresponding generator, in fact, two identical machines may be used, one as generator and the other as motor, the same being true of single-phase alternating, as well as direct-current machines. In all these cases the field magnets must be supplied with direct current either from a separate exciter or from the machine itself, which, if it is an alternator, must be provided with a commutating device for that purpose.

The advantage of the polyphase over the single-phase synchronous motor is the fact that the former is self-starting, owing to the fact that it exerts some rotary effort even when standing still. In this case it acts as an induction motor, the armature being supplied with polyphase current, but the field circuit is left open until synchronous speed is reached. On the other hand, the single-phase motor has no starting torque, and has to be provided with some special device in order to bring it up to synchronism.

The practical forms of induction motor are self-starting with considerable torque, but they are generally arranged with some means for introducing resistance into the secondary circuit, in order to give them full torque when starting, and to prevent a great rush of current at that time.

CHAPTER IX.

TRANSFORMERS.

A TRANSFORMER consists essentially of two separate coils of insulated wire wound or placed upon an iron core. One of these coils, called the *primary*, receives alternating current from some source; and the other coil, called the *secondary*, delivers alternating current to any circuit that may be connected to its terminals. The action depends upon the physical principle that an alternating current sets up an alternating magnetic flux which tends to induce an alternating *E.M.F.* in a conductor that encloses the flux. The function of a transformer is to convert electrical energy at one voltage into electrical energy at another voltage.

For example, a transformer is supplied with an alternating current of 1000 volts and 10 amperes, and it delivers a current of 100 volts and about 97 amperes. The input is 10 k. w., and the output is about 9.7 k.w., since there are losses amounting to about 3 per cent; that is, the efficiency is 97 per cent. In most cases transformers are used to reduce a high-voltage supply of energy into low-voltage energy that is safe and convenient for operating lamps, motors, and other devices. Sometimes they are employed to raise the pressure in order to transmit energy economically over long

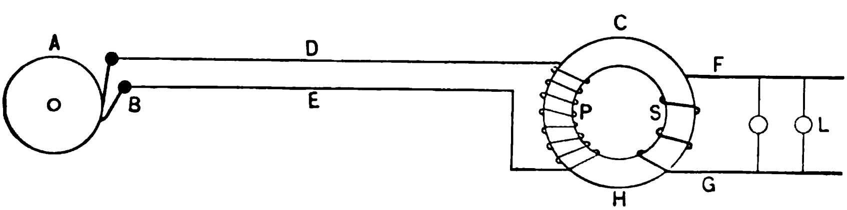


Fig. 122. Simple Transformer Circuit.

lines. The former are called *step-down* and the latter *step-up* transformers. For the sake of simplicity, a transformer is often represented as consisting of a ring of iron, *CH*, in Fig. 122, with a primary coil, *P*, and a secondary coil, *S*, wound upon it. In the

step-down type, which is far more common, the primary, P, is composed of many turns of fine wire, being connected to the high-voltage supply conductors D and E, leading from the alternator, A; and the secondary, S, consists of comparatively few turns of large wire, to which the local or secondary circuit, FG, and lamps, L, are connected. The ratio of voltages of the two coils is substantially the same as the ratio of the number of turns of wire that they contain.

Construction of Transformers. — In practice the arrangement represented in Fig. 122 would not be satisfactory for supplying constant potential to lamps, etc., because the flux produced by the primary P would not all pass through the secondary S, the magnetic leakage across from C to H being considerable, especially when the current in the secondary circuit is large.

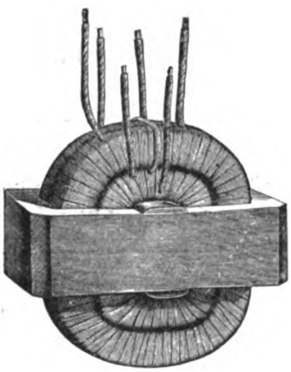


Fig. 123. Transformer with Superposed Coils.

To avoid this magnetic leakage, the primary and secondary coils are placed close together, in many cases being wound one upon the other, as in Fig. 123, which shows the core and coils of a small General Electric type F transformer. In other forms the coils are subdivided and placed side by side alternately, as in Fig. 124, which illustrates a Westinghouse 25 k.w. transformer with the casing removed.

In these and other types of constant potential transformers the object is to reduce the magnetic leakage to a minimum, by so arranging the coils and magnetic circuit that practically all the flux produced by the primary must pass through the secondary. This condition is in conflict with the necessity for very high insulation between the primary and secondary coils to prevent the dangerous high-voltage current from breaking through to the low-voltage circuit. To avoid magnetic leakage, the coils are closely sandwiched together; but to give the best insulation they should be separated. The insulation is obtained, however, by completely covering each coil with several spiral windings of tape and mica-cloth, as represented in Figs. 123 and 125. Sheets of fibre, mica-cloth, etc., are also placed between the coils, in addition to which

special means are generally provided to avoid trouble through failure of insulation. These will be discussed under the head of Transformer Protective Devices.

The coils themselves consist of ordinary cotton-covered round or flat copper wire. These are wound and insulated separately; the proper number and arrangement of primary and secondary coils are then assembled, being held in position by a suitable frame or support. The strips of thin sheet iron (8 to 15 mils = .008 to .015 inch thick) which form the core are next placed around the coils as illustrated in Fig. 125. One method of building up the core is shown in Fig. 126, being the plan followed by the General Electric Company in the larger type *H* transformers. Two different sizes of strips, *A* and *B*, are used, one being longer than the other. A layer of these is laid (Fig. 126); then the next layer is placed so that it breaks joints with the first, as indicated by the dotted lines; and so on until the core is completed, the coils shown in section at *CC* being entirely surrounded by iron, which forms two closed magnetic circuits. The small round holes in the iron strips are slipped over vertical bolts, which serve to locate and hold them in place. A core of the form illustrated in Fig. 123 is generally made of sheet iron punched out in the shape shown in Fig. 127. Each layer consists of a single piece; but it is cut

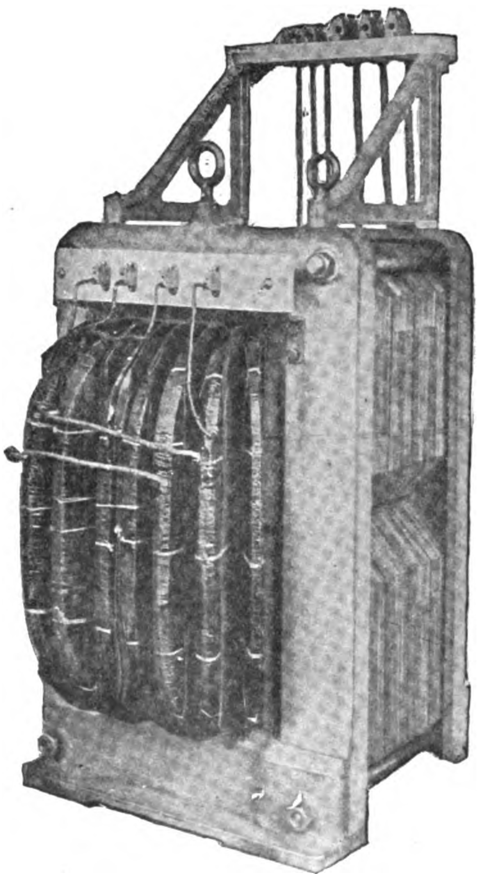


Fig. 124. Transformer with Casing Removed.

through at L and M, forming a tongue, T, which is sufficiently flexible to be put through the coils (Fig. 123). The next piece is placed in the opposite direction, as indicated by dotted lines, in order to distribute the joints in the magnetic circuit.

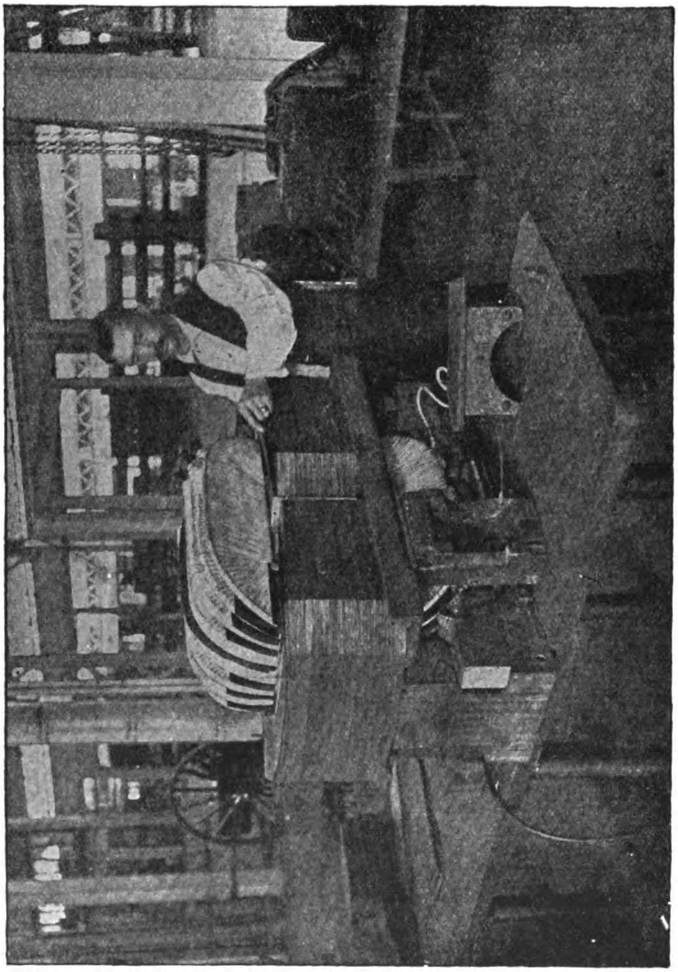


Fig. 125. Method of Building Large Transformer.

For actual use a transformer is enclosed in a cast or wrought iron case to protect it from mechanical injury and dampness. In many instances this case is filled with oil to facilitate the dissipation of heat and to improve the insulation. The Stanley trans-

former (sizes 2 to 10 k. w.) for out-door use, having hanger irons with hooks to fit over cross-arms on poles, is shown in Fig. 128.

Copper Loss in Transformers. — This quantity is simply the heating or $I^2 R$ loss which always occurs whenever any current, I, flows through a resistance, R. If I' is the primary, and I'' the secondary current, R' and R'' being the respective resistances of the primary and secondary coils, then the total copper loss, W_c, in watts is:

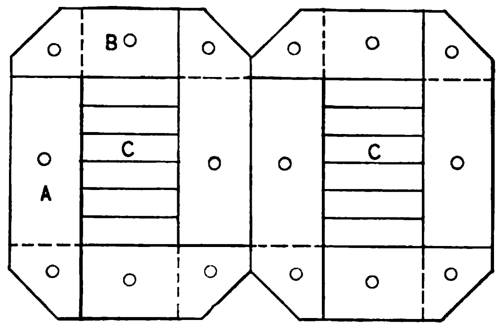


Fig. 126. Transformer Coil.

$$W_c = I'^2 R' + I''^2 R''. \tag{69}$$

Calling W_p the primary input in watts, we have

$$\text{Percentage of copper loss} = \frac{I'^2 R' + I''^2 R''}{W_p}. \tag{69a}$$

From (69) it is seen that this loss varies as the square of the load in amperes. Its exact value depends upon the design of the transformer and working conditions; but in most commercial types at full load it is about 3 per cent for 1 k. w., and about 1 per cent for 100 k. w. capacity. In a very large General Electric transformer having 1875 k. w. output, used at Niagara, the copper loss is a little less than ½ per cent.* It is also evident from (69) that the copper loss increases with the resistance; and since the latter is greater with higher temperature, the loss is larger when the transformer becomes heated by the current or in any other way. The maximum allowable rise in temperature is 50° C. above that of the surrounding air (Amer. Inst. Elec. Eng. Standard); and since the resistance is increased about .4 per cent for each degree, the resistance and copper loss are about $50 \times .004 = 20$ per cent

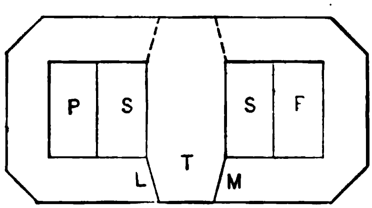


Fig. 127. Transformer Coil.

* *Electrical World and Engineer*, Nov. 18, 1899.

higher at maximum temperature. This point will be considered more fully later under Regulation.

The copper loss injuriously affects the action of transformers in three ways:

1. Copper loss reduces the *efficiency*.
2. Copper loss produces *heat* that may injure the insulation.
3. Copper loss interferes with the *regulation* of constant potential transformers.

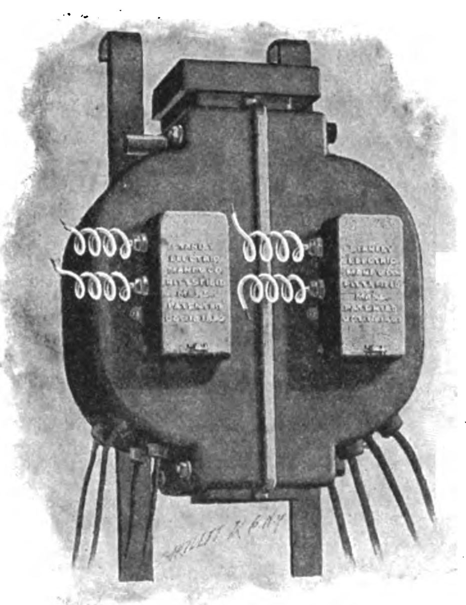


Fig. 128. Transformer for Out-door Use.

Each of these effects will be considered specially under the respective headings, — efficiency, heating, and regulation.

Iron or Core Losses in Transformers. — These are due to hysteresis and eddy currents in the core, and are quite similar to the core losses in a generator or motor. They differ from the copper losses in the fact that they are nearly constant for all loads, whereas we have just seen that the latter vary as the square of load. These statements apply to constant potential transformers, these being by far the most common. The case is exactly the reverse for the constant current type, in which the copper loss in the secondary is constant, and the iron loss varies with the load. In most practical types of transformer the iron losses are about equal to the copper losses at full load. This is not a necessary condition, it being an easy matter to design a transformer in which the iron losses are much greater than the copper losses, or *vice versa*. In fact, they are mutually related, so that increasing one tends to decrease the other.

For general use it has been found best to make the two losses approximately equal; but for special cases, where constancy of voltage is important, or where transformers operate with considerable load most of the time, the copper loss may be reduced at the sacrifice of increased iron loss. If, however, constant voltage is not important, and a transformer is likely to run at light loads a great part of the time, then the iron loss should be diminished at the expense of the copper loss. Ordinarily these differences require transformers to be specially designed for the purpose; but variations in frequency, voltage, or other conditions will alter the relation between the two losses.

The hysteresis loss in watts, W_h, is:

$$W_h = \eta\, V f B^{1.6}. \tag{70}$$

In this expression, V is the volume of the iron core in cubic centimeters, f is the frequency in cycles per second, B is the maximum flux density in lines per square centimeter, and η is a constant depending upon the quality of the iron. For high-grade annealed sheet iron suitable for transformer and armature cores, the value of η is usually between 2×10^{-10} and 3×10^{-10}. In calculations where the exact value is not known, an average value of 2.5×10^{-10} may be assumed. The ordinary values of B, the maximum flux density, for various sizes of transformer and frequencies are given on page 157.

Ageing of Transformer Iron. About 1894 attention was called to the fact that the iron cores of transformers became changed after being used for some time, the hysteresis loss increasing considerably. Investigations showed that the core loss of some commercial types of transformers rose to two or more times the initial value after a few months' operation. It was found that this was due to heat, the same effect being produced by heating the iron in any other way. This phenomenon depends upon the mechanical and chemical character of the iron, but the exact effect of the different impurities has been found to be difficult to determine. By experience and the exercise of great care, manufacturers have been able to avoid this increase of hysteresis loss, so that transformers made at present have very little more core loss after long periods of use. Professor W. E. Goldsborough has given * the results of

* Paper before National Electrical Light Association, May, 1899.

tests made on several of the most prominent types of transformer, and these show that the core loss remained practically constant for 800 hours at full load. These tests were made in a room where the temperature was about 25° C., and the full load was applied for ten and a half hours a day. This is fully as severe as ordinary practical service; nevertheless, the temperature of the cores did not exceed 75° C., allowing the standard rise of 50° C. Up to this point it is found that the ageing effect does not occur; but above 80° it begins, and at 100° it becomes considerable, increasing with the temperature up to about 200°, beyond which it falls again.

The conclusion is, that transformer cores should not be run, even for a short time, at temperatures exceeding 80° C. At full load the allowable rise is 50° C.; hence the room temperature must not be greater than 30° C., or 86° F. On the other hand, in very hot weather, or in an engine-room where the temperature may be 10 or 20 degrees higher than this, transformers should not be run at full-load, or may be operated for shorter periods of time, so that they do not attain maximum temperature. This matter is sufficiently important to demand attention, and every one installing or using transformers should guard against the possibility of the core temperature rising above the point at which ageing begins. This limit may be ascertained from the makers.

The eddy or Foucault current loss in the core in watts, W_e, is

$$W_e = b\ V f^2 t^2 B^2. \qquad (71)$$

In this expression t is the thickness of the laminations in centimeters; V, f, and B have the same significance as in (70), and b is a constant depending upon the specific resistance of the iron. In the iron ordinarily used the value of b is about 1.6×10^{-11}.

In a paper read before the American Institute of Electrical Engineers, May, 1900, Mr. Fitzhugh Townsend claims that the eddy current loss is proportional to $B^{1.6}$ instead of B^2.

This equation assumes that the sheets of iron forming the core are properly insulated from each other, otherwise the loss is greater, because the eddy currents flow from one sheet to another as if the core were a solid mass of iron.

Since the eddy current loss in (71) varies as t^2, the square of the thickness of the iron plates, it may be reduced to a very small value by making them very thin. On the other hand, the insula-

tion and unavoidable space between the plates is about 2 mils, so that in practice a thickness of 10 to 15 mils is generally adopted in order that the proportion of iron in the total volume of the core shall be high. Assuming an ordinary thickness of 12 mils for the plates and a distance between them of 2 mils, the actual iron in the core is $\frac{12}{12+2} = .86$ of the total volume. With these relations the eddy current loss constitutes about 20 per cent of the core loss, the hysteresis loss making up the remaining 80 per cent. In some cases the thickness of plates is reduced to 7 or 8 mils, so that the eddy current loss is only 8 or 10 per cent of the core loss; but this tends to increase the volume of the core as well as the weight of copper, and involves more labor in construction, hence the final gain is doubtful.

The permissible rise in temperature being 50° C., the resistance of the iron core increases about 20 per cent after a long run at full load, hence the eddy current loss is reduced in the proportion 120: 100, or in other words it is about 17 per cent less. But the eddy current loss is only about 20 per cent of the iron loss, so that the latter is reduced 3 or 4 per cent at full working temperature, hysteresis being constant.

Flux Densities in Transformer Cores. The hysteresis loss varies as $B^{1.6}$ in (70) and the eddy current loss as B^2 in (71) or B^{16}, in which B is the flux density, consequently the latter is kept at a low value in transformers in order that the core loss shall be small. Different designers adopt various densities, average figures being given in the following table.

ORDINARY FLUX DENSITIES IN TRANSFORMER CORES.

MAXIMUM LINES PER SQUARE CENTIMETER.

Frequency.	1 to 5 k. w.	10 to 25 k. w.	100 to 500 k. w.
25	7500	6500	5500
40	6500	5500	4500
60	5000	4500	4000
100	4000	3500	3000
120	3500	3000	2500

The density is decreased with higher frequency in order to keep the iron losses in (70) and (71) nearly the same for a given volume of core. These densities are much lower than those

allowed in the armature cores of generators and motors which are often as high as 15,000 or 16,000 lines per square centimeter. The reason for this is the higher efficiency of 97 or 98 per cent which is expected of transformers compared with 92 to 94 per cent for machines. The former often operate for long periods at very light load, while generators usually have one-half to full load while they are running, consequently the constant core loss is a more serious matter in transformers.

Exciting Current. When the secondary circuit of a transformer is open and the primary circuit is closed, a certain current flows in the latter. This is called the *exciting current*, being also known as the *leakage current*, *open-circuit current*, and *magnetizing current*. It consists of two components, one of which supplies the energy to make up the transformer losses, and the other produces the magnetization of the core. The former represents true power in watts being practically equal to the iron losses, and the latter is apparent power being wattless. The total value of the exciting current depends upon the design and size of the transformer, but is ordinarily about 5 per cent for 1 k. w., and about 2 to 1 per cent in sizes of 25 to 100 k. w. or larger.

The power factor of the exciting current at no load differs considerably in the various types, but is usually about 70 per cent. Since this is equal to the cosine of the angle of lag, it follows that the no-load primary current lags about 45° with respect to the primary impressed *E.M.F.* It is evident also that the energy component of the current is about equal to the magnetizing component. When a transformer is loaded even slightly, for example, to one-tenth of its normal capacity, the power factor rises to very nearly 100 per cent, and the primary current is practically in phase with the primary impressed *E.M.F.*, provided the load is non-inductive, which is usually the case in electric lighting. If, however, induction motors or other forms of inductive load are present, the power factor will be less than 100 per cent, and the current will lag behind the *E.M.F.* as in any alternating-current circuit.

The above statements apply to transformers having *closed* magnetic circuits. In the so-called "hedgehog" type with open magnetic circuit consisting of a simple straight core, the no-load exciting current is about ten times as great, being more than one-half of the full load value in a 3 k. w. size, with a power factor of

only .063, which is also about one-tenth as much as for closed magnetic circuit.* On account of its low-power factor this large exciting current does not involve directly any greater loss of power in true watts. But it uses up the current capacity of the generators, lines, etc.; the heating effect and drop for a wattless current being the same as for any other current having the same value in amperes. Furthermore, it reacts injuriously upon the regulation of generators and transformers, greatly increasing their drop in volts. For these reasons the closed magnetic circuit has been adopted almost universally. In fact, the greatest care is exercised in making the magnetic circuit as complete as possible, the effect of joints being reduced to a minimum, which also reduces magnetic leakage, as explained on page 150.

To prevent the flow of this exciting current, magnetic cut-outs have been devised to open the primary circuit automatically when the secondary circuit is open. It is objectionable, however, to open and close the primary (high voltage) circuit whenever the load is thrown off or on, so that this arrangement is seldom used in practice. Another plan is to open the primary lines at the station during the hours that the current is not required. This is customary in smaller systems, and is possible on certain circuits of large systems, but it cannot be applied generally in important plants.

Efficiency of Transformers. The efficiency of a transformer is the ratio of the watts output W_s measured at the secondary terminals to the watts input measured at the primary terminals W_p. Since the losses occurring in a transformer are: W_c the copper loss from (69), W_h the hysteresis loss from (70), and W_e the eddy current loss from (71), it follows that the output is equal to the input minus these losses, hence

$$\text{Efficiency} = \frac{W_s}{W_p} = \frac{W_p - (W_c + W_h + W_e)}{W_p} \qquad (72)$$

The efficiency is very high for transformers made by the best manufacturers, being about 98 per cent at full load for sizes of 25 k. w. or larger, and 94 or 95 per cent at one-quarter load. This is higher than the efficiency of almost any other practical apparatus, nevertheless it is found that the aggregate losses are large, and form a heavy item in the cost of alternating-current supply, because

* *The Alternate Current Transformer* by J. A. Fleming, London, 1896, p. 567.

transformers run for a large part of the time with small loads, especially in electric lightning.

Calculation of Transformer Efficiencies. Knowing the iron and copper losses at any given load, it is a simple matter to calculate these losses and consequently the efficiency at other loads. For example, a 10 k. w. constant-potential transformer at full rated load and temperature has a copper loss of .16 k. w. or 1.6 per cent, the iron loss being the same. Since transformers and most other apparatus are rated by their output, the efficiency would be

$$\frac{\text{output}}{\text{input}} = \frac{10}{10 + .16 + .16} = 96.9 \text{ per cent.}$$

At three-quarters load the output is 7.5 k. w., the iron loss is the same as before, being practically constant; the copper is proportional to the square of the load, or $\frac{3}{4} \times \frac{3}{4} \times .16 = .09$ k. w., so that the efficiency would be $\frac{7.5}{7.5 + .16 + .09} = 96.8$ per cent. Calculating in a similar manner the efficiencies at other loads, we obtain the following results:

$$\text{Efficiency at } 25\% \text{ overload} = \frac{12.5}{12.5 + .16 + .25} = 96.8\%$$

$$\text{" \quad " rated load} = \frac{10}{10 + .16 + .16} = 96.9\%$$

$$\text{" \quad " three-quarters load} = \frac{7.5}{7.5 + .16 + .09} = 96.8\%$$

$$\text{" \quad " one-half load} = \frac{5}{5 + .16 + .04} = 96.2\%$$

$$\text{" \quad " one-quarter load} = \frac{2.5}{2.5 + .16 + .01} = 93.3\%$$

$$\text{" \quad " one-tenth load} = \frac{1}{1 + .16 + .0016} = 86.1\%$$

$$\text{" \quad one-twentieth load} = \frac{.5}{.5 + .16 + .0004} = .75.7\%$$

In order to bring out the comparative effects of the two losses, let us calculate the efficiencies of two other transformers, one having a copper loss of .08 k. w. and an iron loss of .24 k. w., the other having .24 k. w. copper loss, and .08 k. w. iron loss. In

all three cases the sum of the losses is assumed to be the same at full load (10 k. w.), being .32 k. w. The results are given in the following table:

EFFICIENCIES OF TRANSFORMERS WITH DIFFERENT RATIOS OF LOSSES.

Losses in K. W.		Output in K. W.						
Copper	Iron.	12.5	10.	7.5	5.	.25	.1	.05
.16	.16	96.8	96.9	96.8	96.2	93.3	86.1	75.7
.08	.24	97.1	96.9	96.3	95.1	91.2	80.6	67.6
.24	.08	96.4	96.9	97.2	97.3	96.3	92.4	86.1

The above efficiencies as well as the losses at different loads are plotted as curves in Fig. 129. A study of the table and curves brings out many important points regarding transformers:

1. The sums of the losses being equal (.32 k. w.) at rated load (10 k. w.) the efficiencies are the same for that particular output.

2. Transformer No. 1, with copper and iron losses equal at rated output, has an efficiency which is a maximum at that point, and is nearly constant (96.2 to 96.9%) from one-half load to 25 per cent overload, being well suited to this range.

3. Transformer No. 2, with large iron loss which is constant, has maximum efficiency with considerable overload (about 50%), but is low in efficiency below three-quarters load. Its small copper loss, however, makes its regulation excellent, the resistance drop being only .8 per cent at rated load.

4. Transformer No. 3, with small iron loss, has opposite characteristics, its efficiency being highest at one-half load, and 92.4 per cent at one-tenth load, which is remarkably high. At overload the efficiency falls rather rapidly. The regulation is not good, since the resistance drop alone is 2.4 per cent at rated output. It would be adapted for power or other use where the load was light most of the time, and where such a variation in voltage is not objectionable.

5. From the point of view of efficiency only, the copper loss in constant potential transformers is less objectionable than iron loss for variable load, since the former varies as the square of the current, and thus adjusts itself to the working conditions. This is shown by comparing Nos. 2 and 3; the latter with relatively large copper loss has an efficiency of 92.4 per cent at one-tenth

load, while the efficiency of the former, with very small copper loss, is only 80.6 per cent.

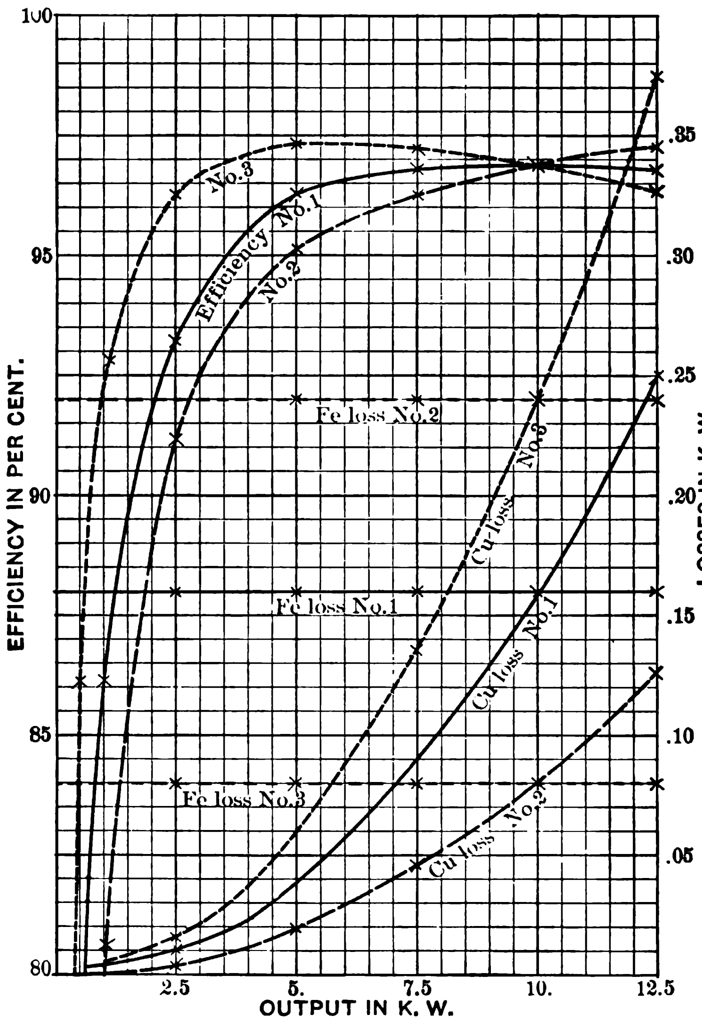


Fig. 129.

6. On the other hand, the effect upon regulation is exactly the reverse, as set forth on page 164.

The calculations of efficiency as made above might be criticised on the ground that the increase in resistance due to temperature rise at full load, is not taken into account.

The resistances of primary and secondary coils were taken in all cases as constants, the value being that for continuous running at rated load commonly called the resistance "hot." This makes the calculated efficiency correct at that load, and the error would be slight for other loads. For example, the efficiency of No. 1 at half-load is given as 96.2 per cent, and with allowance for reduced temperature it would become 96.25 per cent. The difference is so insignificant that it does not warrant the trouble in making the correction.

The reason why the discrepancy is not larger is to be found in the fact that the copper loss at light loads is much reduced, and a small variation in it has very little effect.

Furthermore, the heating is only partly (about one-half) due to the copper loss, so that the temperature does not change in proportion to it. The conclusion is that the resistances "hot" (at full load) may be taken to calculate efficiencies at any continuous load from zero to 25 per cent overload with very trifling error.

All-day Efficiency. Since the efficiency of transformers varies considerably with the load, as shown in Fig. 129, it is evident that the changing output which occurs in practical working will give an average or all-day efficiency which is usually less than the maximum. For purposes of comparison, the transformer is assumed to run fully loaded for 5 hours, and with no load for the remaining 19 hours. On this basis the all-day efficiency is commonly reckoned; but in any case where the actual periods and amounts of output are known, the determination can be made accordingly. Applying the conventional 5 hours full load and 19 hours no load to the three transformers whose efficiency curves are shown in Fig. 129, we find the following:

ALL-DAY EFFICIENCY OF TRANSFORMERS.

	Iron Loss in K. W. Hours.	Copper Loss in K. W. Hours.	Total Losses in K. W. Hours.	Total Output in K. W. Hours.	All-Day Efficiency. Per Cent.
No. 1 . .	$24 \times .16 = 3.84$	$5 \times .16 = .8$	4.64	$5 \times 10 = 50$	91.1
No. 2 . .	$24 \times .24 = 5.76$	$5 \times .08 = .4$	6.16	50	89.0
No. 3 . .	$24 \times .08 = 1.92$	$5 \times .24 = 1.2$	3.12	50	94.1

This table demonstrates that transformer No. 3 with small iron loss which is constant has a very high all-day efficiency of 94.1 per cent, while No. 2 with large iron loss has only 89 per cent. The losses per day of No. 2 are 6.16 k.w., being nearly twice those of No. 3, which are 3.12 k.w. In the course of a year, the total output of each transformer would be $365 \times 50 = 18250$ k.w. hours, and the losses of No. 2 would amount to $365 \times 6.16 = 2248.4$ k.w. hours, or one-eighth as much as the output. The losses in No. 3 are about one-half as great, so that it secures a saving of over 1100 k.w. hours per annum for a single 10 k.w. transformer.

If the copper and iron losses at full load are known, the all-day efficiency of any transformer is easily calculated, as shown in the table. The iron loss, being constant, is found for the whole 24 hours, and the copper loss for the particular loads and periods of operation. The sum of these losses is added to the calculated output to give the input, and the former divided by the latter is the efficiency.

Regulation in Transformers is the percentage of fall in secondary voltage from no load to full load for constant potential working. The constant current transformer will be considered under that special heading. The potential difference between the secondary terminals is less at full load, than at no load, on non-inductive load being chiefly due to the resistance drop in both the primary and secondary coils. Calling I' and I'' the primary and secondary currents, R' and R'' the resistances of the primary and secondary coils, E' and E'' the primary and secondary *E.M.F*s. respectively, being practically the terminal voltages measured at no load, we have

$$\text{Percentage of resistance drop in primary} = \frac{I' R'}{E'} \tag{73}$$

$$\text{" \quad " \quad " \quad " \quad " secondary} = \frac{I'' R''}{E''} \tag{74}$$

$$\text{Percentage of total resistance drop} = \frac{I' R'}{E'} + \frac{I'' R''}{E''} \tag{75}$$

If both numerator and denominator in (73) be multiplied by I' we have $\frac{I'^2 R'}{E' I'}$ which is the percentage of primary copper loss in watts compared with total primary input in watts. The value of

this latter fraction must be the same as that in (73), hence *the percentage of copper loss in watts is the same as the percentage of resistance drop in volts.* This applies to primary or secondary circuits and to total values.

In addition to the drop due to resistance, the regulation or total fall in voltage is aggravated by the magnetic leakage at full load. In well-designed transformers, great care is taken to make this latter factor a minimum by arranging the coils and core as explained in connection with Figs. 123 and 124. The result is that the diminution of secondary voltage caused by magnetic leakage is only about ten per cent of that due to resistance. Since the latter is usually from 1 to 3 per cent for large and small transformers respectively, the total fall in voltage, that is, the "regulation," is .1 to .3 per cent greater. We have just seen that copper loss and resistance drop are equal percentages, hence the regulation may be considered as having about the same value, being only one-tenth greater in most practical instances.

The resistance increases with the load on account of heating, the maximum allowable rise in temperature being 50° *C.* (Amer. Inst. Elec. Eng. Standard), which would augment the resistance about 20 per cent. If full load is applied to a transformer, the resistance drop will increase about 20 per cent after a run sufficiently long to give the maximum temperature. Therefore the regulation and the copper loss when "hot" are about 20 per cent greater than when "cold." Both values are often given, but the former is generally the proper one to consider, the other representing merely a temporary condition. In calculating efficiency, it has been shown on page 162 that this variation makes very little difference, since the losses are only partly due to resistance; but regulation is directly proportional to the latter, and any change in one produces a corresponding change in the other.

The time required for a transformer to reach maximum working temperature depends upon its size and construction, being usually between 6 and 18 hours. For this reason a transformer that operates at full load for shorter periods might properly have its regulation and efficiency determined after an ordinary run.

Although the regulation of transformers appears to be good, the drop at full load being only 1 to 3 per cent, nevertheless it is a serious difficulty in alternating current distribution. This is

because it is in *addition* to variations in the generator, lines, etc., which occur on any electrical circuit. Even if hand or automatic regulation at the station counteracts any drop in the generator and lines, it is impossible to overcome the drop in each transformer, since one may be heavily, and another lightly, loaded on the same circuit. Being about equal to the drop in the house wiring, it doubles the *local* fall in voltage. For example, a loss of 2 per cent in the wiring would not be very noticeable, but a variation of 4 per cent is objectionable. What is needed is some means of raising the secondary voltage automatically with increase of load, that is, something similar to compound winding in a generator. This might be made to compensate for the drop in the transformer, and in the wiring as well. Unfortunately no such device has yet been applied practically. The various methods of regulation employed for alternating current systems will be described in the next chapter, but none of them overcome this particular trouble.

Another difficulty in this connection is the fact that the drop in a transformer is aggravated by inductive load. For example, a transformer which falls only 2 per cent in voltage at full non-inductive load, will have a drop of about 4 or 5 per cent with a full load having a power factor of 80 per cent. With lower power factors which often obtain in practice, the regulation would be still worse.

Methods of Cooling Transformers. The total iron and copper losses, ordinarily amounting to 2 to 4 per cent, appear as heat in the core and coils; and since this production of heat goes on continuously so long as a transformer is in operation, some means must be provided to prevent the temperature from rising above a certain safe limit. With small transformers their surface is relatively large compared with the heat produced, so that the latter is dissipated by radiation, conduction, and convection sufficiently fast to prevent excessive rise in temperature even for a continuous run at full load. In larger transformers the losses increase more rapidly than the surface, so that some special means must be provided for cooling them. These losses are by no means inconsiderable; a 100 k.w. transformer, for example, having about 2 k.w. loss, which is sufficient energy to supply forty 16 c.p. lamps. The more rapidly that heat is taken away from a transformer, the greater may be its output without exceeding the allowable temperature rise. In other words, smaller quantities of iron and copper

are required for a given capacity in k.w. if effective means of cooling are provided.

METHODS OF COOLING TRANSFORMERS.

1. Self-cooling dry transformers.
2. Self-cooling oil-filled transformers.
3. Transformers cooled by forced current of air.
4. Transformers cooled by forced current of water.
5. Transformers cooled by combination of above means.

Self-cooling dry transformers. It has just been explained that smaller sizes do not require any special means of cooling, since their surface is relatively large. Some larger types up to 50 k.w. are also made in this way; but, as stated above, they are heavier and more expensive than the following forms.

Self-cooling, oil-filled transformers are very generally employed, the entire core and coils being immersed in oil. Transformers are practically always enclosed in a cast or sheet iron case, and this is simply filled with oil. No increase in cooling surface is thereby secured, but the natural circulation of the oil tends to equalize the temperature of the various parts, and carries the heat to the case from which it is dissipated. In most self-cooling types the case is made with external ribs or corrugations to increase its surface. The large volume of oil also absorbs considerable heat, so that the temperature rises more slowly; hence for moderate periods of operation up to 3 or 4 hours, which is ordinarily sufficient in electric lighting, the maximum temperature would not be reached. Another advantage gained by this arrangement is an improvement in insulation. This is due to the high insulating qualities of the oil itself, and to the fact that a disruptive discharge takes place through it much less readily than through the air that it displaces, distances being the same. It possesses, moreover, the power of self-repairing any break in the insulation. If ordinary materials, such as cloth or mica, become punctured, they lose their insulating properties, and the apparatus cannot be used until the fault is repaired, which ordinarily involves considerable time and expense. On the other hand, if oil is punctured, it tends to close in and repair the break, unless the discharge lasts so long that a charring occurs, which may make a permanent conducting path.

The chief objection to the use of oil is the danger of fire. If a short-circuit occurs inside of the transformer, the oil may be

thrown out and ignited at the same time, or a fire started in some other way might be made far more disastrous by the presence of a large quantity of oil. In this way several plants have been destroyed by fire with large loss of property. There is no special precaution that will entirely eliminate this risk; but care in locating such transformers, in avoiding overheating, and in protecting them by effective lightning arresters, will reduce the hazard.

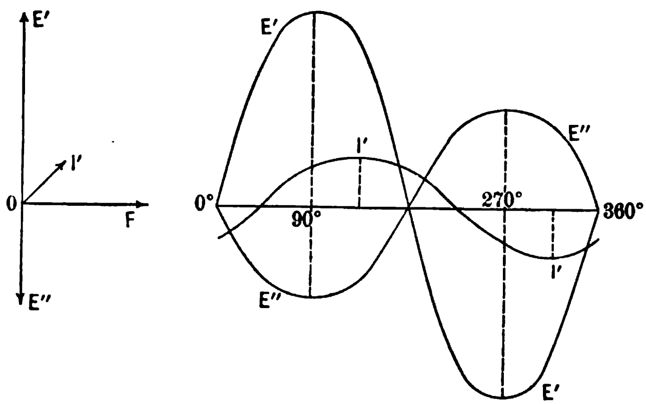
Air-blast transformers are now commonly employed, and have the advantages over the oil-cooled type, that the danger of fire is avoided, and the cooling effect may be regulated in accordance with the working conditions. They are so constructed that air can circulate through and around the core and coils, the ventilation being forced by a blower driven by a motor. A transformer of 100 k.w. capacity requires about 350 cubic feet of air per minute at a pressure of .4 ounce per square inch, the power consumed being less than $\frac{1}{10}$ of one per cent of the full-load output of the transformer. The flow of air is controlled by dampers, and the proper amount may be determined from its temperature as it issues from the top; ordinarily this should not be more than 20° *C.* above that of the atmosphere.

Water-cooled transformers are also oil-filled in most cases. A continuous flow of cool water is maintained through pipes immersed in the oil, through a water jacket formed in the casing, or through the conductors (primary or secondary) themselves if they are sufficiently large. It is the most effective method of cooling, and is very convenient for water-power plants, the supply and pressure being at hand. Where a natural flow is not available, pumps or the city water mains may be utilized. It is found that about ½ gallon of water per minute is sufficient for a 150 k.w. transformer. This type requires the least weight of iron and copper for a given output, since its heat is carried away most rapidly.

Instead of having a flow of water, the oil itself may be drawn off, cooled, and then returned by means of a pump driven by a motor. In any of these types of transformers depending upon forced circulation of air, water, or oil, it is vitally important to avoid any stoppage of the flow, as it is likely to cause a burn-out.

Phase Relations in Transformers. If E' a certain alternating *E.M.F.* is impressed upon the primary coil of a transformer, a

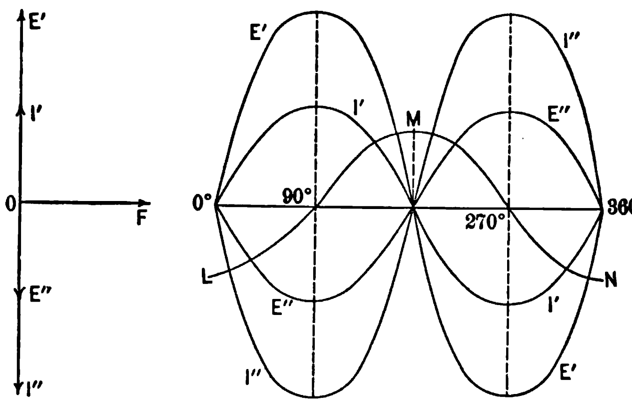
primary current I' flows, which sets up an alternating flux in the iron core. This in turn induces an alternating $E.M.F.$ in the secondary coil, which produces a current provided the secondary circuit is closed. The secondary $E.M.F.$ E'' is almost exactly opposite in phase to E' the primary $E.M.F.$, as represented in Figs. 130 and 131. If the secondary circuit is open, the primary current I', which is then called the exciting current, lags behind E' a certain amount, being usually about 45° as indicated. When the secondary circuit is closed, and any current greater than one-tenth of full load flows in it, the primary current I' is brought very nearly in phase with E', so that the power factor is practically 100 per cent provided the secondary circuit is non-inductive; these conditions



Figs. 130 and 131. Transformer Phase Relations.

being shown in Figs. 132 and 133. The magnetization M. (i.e. alternating flux) in the core differs in phase by 90° from E' and also from E''. In other words, the maximum flux occurs one-quarter period later than the maximum impressed $E.M.F.$ This is because the $E.M.F.$ is zero when the flux is a maximum and does not vary (at 180° in Fig. 133); also the $E.M.F.$ is highest when variation of flux is most rapid (at 270° in Fig. 133). The magnetization is nearly constant for all loads, except that it decreases slightly at heavy load, owing to magnetic leakage. Consequently the ratio of transformation ($E' : E''$) is nearly constant, being practically equal to the ratio of the number of turns in the primary and secondary coils. For simplicity in the diagrams, E'' is made one-half of E', so that I'' would be about twice as great as

I' since the secondary watts are almost equal to the primary watts, the efficiency being 96 to 98 per cent. In the primary circuit, besides the impressed *E.M.F.*, we have the *E.M.F.* of self-induction and of mutual induction. With open secondary, there is no mutual induction, and the *E.M.F.* of self-induction is opposed and nearly equal to the impressed *E.M.F.*, so that very little current flows, usually only 1 to 3 per cent of full load. But when current is drawn in the secondary, the *E.M.F.* of mutual induction rises and tends to neutralize the *E.M.F.* of self-induction, so that the primary current increases proportionally. These constitute the main physical quantities involved in the action of a transformer; but in addition there are certain other factors which



Figs. 132 and 133. Transformer Phase Relations.

are smaller, but play parts of some importance. One of these is the *magnetizing current* which overcomes the reluctance of the core. This lags 90° behind E' the impressed *E.M.F.*, and is therefore wattless. The current which supplies the core loss (hysteresis and eddy currents) is the other component of the exciting current I' in Fig. 130. It is in phase with E', and represents real power. In practice these two components are usually about equal, producing approximately 45° lag with no load.

The resistance drop in voltage in the primary and secondary coils ($I'R'$ and $I''R''$) are also small quantities which must be considered, since they affect the regulation as already explained under that head. The primary resistance drop is usually ½ to 1 per cent of the primary *E.M.F.*, and the same for the secondary.

Their effect at full load is to increase the apparent ratio of transformation as measured at the terminals, in practice producing a fall in secondary voltage corresponding to their sum.

Magnetic leakage is still another small quantity that affects the action of a transformer. It interferes with the regulation by increasing the fall in secondary voltage usually about ¼ per cent, with full non-inductive load as stated on page 165, and more than this, with inductive loads. Its effect is similar to that of inductance introduced in the primary circuit.

Inductance in the secondary circuit produces a lag of secondary current behind secondary *E.M.F.*, the same as for other alternating current circuits, the angle being shown in Fig. 82. This produces a corresponding lag in the primary circuit, so that the power factors of both are reduced, being equal to the cosine of the lag angle. The regulation is made much poorer by this condition, the drop in secondary voltage being increased from 1 per cent with non-inductive load to 2½ per cent with .90 power factor or 26° lag. In fact, this causes serious trouble when there are induction motors or other inductive load on the same circuits with lights.

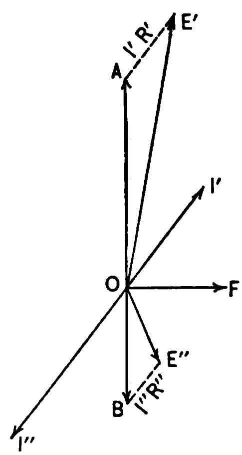


Fig. 134. Transformer Phase Relations.

Resistance drop with lagging current is represented in Fig. 134, in which OA is the useful portion of the impressed *E.M.F.*, OB is the total *E.M.F.* induced in the secondary coil, OI' is the primary and OI'' the secondary current, OF being the phase of the magnetization. The primary resistance drop $I'R'$ is in phase with the primary current I', and similarly $I''R''$ is in phase with I'', hence the impressed *E.M.F.* is OE', and the secondary *E.M.F.* is OE''. The ratio of transformation at no load is $OA \div OB$, and at full load it is $OE' \div OE''$, which is considerably greater, so that the secondary voltage must fall if the impressed *E.M.F.* is constant.

Constant Current Transformers. For the operation of arc or incandescent lamps on series circuits an approximately constant current is required. In direct current distribution this is produced by the Brush and other well-known types of self-regulating dyna-

mos. Corresponding machines have been designed for the alternating current, but it is a more common practice to obtain a constant alternating current from the secondary circuits of special forms of transformer, the primary circuits of which are supplied in parallel at constant potential. A prominent example is the General Electric constant current transformer illustrated in Figs. 135

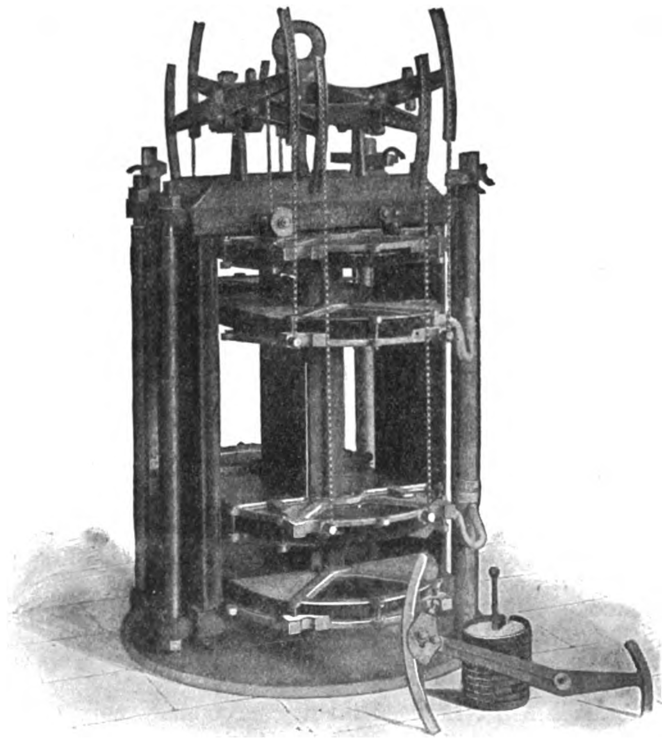


Fig. 135. Constant Current Transformer.

and 136. In its simplest form, it consists of a core of the double magnetic circuit type with three vertical limbs, and two flat coils placed around the central limb. The lower coil, usually the primary, is fixed, while the upper is suspended and balanced so that it can move up and down a considerable distance. The larger transformers have one fixed primary below, and another above with two secondary coils which are balanced on levers and move in opposite

directions, as shown in Fig. 135. Very large sizes sometimes have four sets of coils with a single magnetic circuit.

When currents flow in the primary and secondary coils, a repulsion is produced between the coils, so that they tend to move away from each other. For a given secondary current (usually 6.6 amperes for enclosed arcs), the repulsion is balanced by a certain weight, so that any increase in current due to cutting out of lamps in series causes the coils to separate, and *vice versa*, thus automatically maintaining a nearly constant current. The quadrants on the levers are made adjustable, because the repulsion for a given current is not the same for all positions of the coils, being greater when they are close together. This enables the current to be kept almost exactly constant from one-third to full load, but in practice these transformers are usually adjusted so that the current at half load is 10 per cent less than at full load. This is done because the wave form of most alternators produces an increase in voltage at the lamps when the constant current transformer is working on light loads. The full-load efficiency varies from about 96.5 per cent for 100-light transformers to about 94.5 per cent for 25-light transformers. The whole apparatus is placed in an iron case with corrugations to increase the cooling surface, which is filled with oil in order to carry away the heat, increase the insulation, and serve as a dash-pot to prevent too rapid movement of the coils.

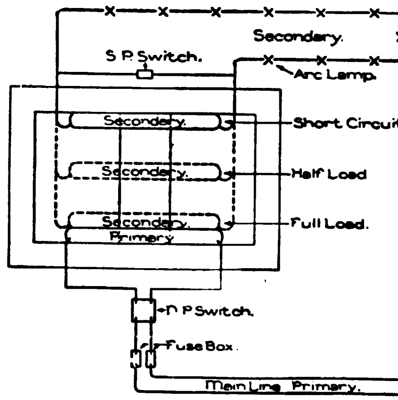


Fig. 136. Constant Current Transformer.

These transformers will operate without much attention, and may be placed in the stations where the current is generated, in sub-stations, or, if specially designed, in manholes under the street.

Two 100-light transformers of this kind tested by Professor W. L. Robb and described by him in a paper on this subject * gave the following average results :

* Transact. Amer. Inst. Elec. Eng., September, 1899.

Load.	Efficiency.	Power Factor.
One-quarter	88.1 per cent	24 per cent
One-half	92.3 " "	44 " "
Three-quarters	94.9 " "	62 " "
Full	96.1 " "	78 " "

The low power factor and efficiency at small loads make it undesirable to operate these transformers below 70 or 80 per cent of their rated capacity. In street-lighting, for which they are most often used, the load is generally at least 80 or 90 per cent of the full amount, hence this objection does not apply.

Other forms of constant current transformer have been designed by the Fort Wayne Company and others, the coils being stationary, and the regulation being due entirely to magnetic leakage and resistance drop. In this case the leakage, which is most carefully avoided in constant potential transformers, is purposely exaggerated by the arrangement illustrated in Fig. 137. Any rise of current in the secondary coil S tends to "blow out" the flux produced by the primary coil P, the magnetic leakage across the air-gap G increasing at the same time. This tends to prevent the secondary current from varying, even though the resistance in the secondary circuit is altered considerably. In such a transformer the current does not rise more than 10 per cent when the load (i.e., number of lamps in series) is increased from one-quarter to full value.

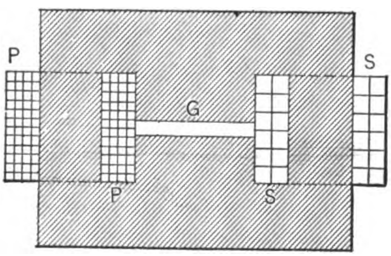


Fig. 137. Constant Current Transformer.

The methods of connecting and operating these transformers will be discussed in the next chapter.

Protective Devices for Transformers. In almost all cases the primary and secondary circuits of transformers are designed to operate at widely different voltages. For electric lighting the ordinary primary pressure is about 2000 volts, and the secondary about 100 or 200 volts. In long distance transmission the higher pressure may be 10,000 to 30,000 volts, or even more. Evidently it is a very serious matter if, by failure of insulation or other cause, the high-voltage current breaks through to the low-voltage circuit. The latter is not, and in practice cannot be, sufficiently well insu-

lated to withstand the effects of the high pressure. Moreover, the danger to persons is very great, since the presence of the deadly current is likely to be entirely unexpected. There would be little object in using a transformer if the low-tension circuit had to be treated with the same precautions as the high-tension. In fact, this is a grave difficulty in the operation of transformers. The high-voltage may break or leak through to the low-voltage circuit, either on account of defective insulation between the primary and secondary coils inside of the transformer, or it may occur through accidental contact of the primary and secondary conductors outside of the transformer. In either case the trouble is often due to, or developed by, lightning or other atmospheric electrical discharges. For this reason transformers working on overhead lines are more likely to have difficulties of this kind than those used in connection with underground wires.

The principal means employed to avoid or mitigate the effects of interconnection between primary and secondary circuits of transformers are:

1. Tests of insulation by manufacturer.
2. Lightning arresters.
3. Devices for automatically grounding the secondary circuit when its pressure rises abnormally.
4. Grounded metallic shield interposed between primary and secondary circuits.
5. Permanent grounding of secondary circuit.
6. Test wires run from the station to the secondary circuits of transformers.
7. Periodical testing of transformer insulation by extra high pressure to develop latent faults.
8. Insulation tests of primary circuits of system.

All transformers should be tested for insulation strength by their manufacturers. A testing pressure at least twice the rated voltage, *i.e.*, twice the higher voltage, should be applied for not less than one minute. Tests are made between the primary and the core or case, and between the primary and secondary coils. In very high-voltage transformers (10,000 to 20,000 volts) it is sufficient to connect at rated pressure first one and then the other terminal of the high-voltage winding to the core and to the low-voltage winding. This subjects the insulation to twice the normal pressure.

Lightning Arresters are described in Vol. I. Chapter XXIV. In connection with transformers they are very important, as many of the cases of break-down of insulation are caused by atmospheric electricity.

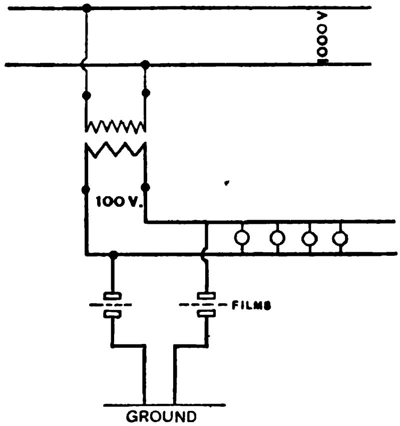


Fig. 138. Automatic Grounding Device.

The automatic grounding of the secondary circuit by abnormal rise in its voltage is accomplished by various devices. One of these commonly used in England is the "Cardew earthing-device." It consists of two horizontal brass plates, insulated and separated from one another by ¼ inch of air space, the upper being connected to the secondary circuit of the transformer, and the lower being well grounded. A thin strip of aluminum foil is attached at one end to the lower plate and rests upon it. A lug on the upper plate approaches to within $\frac{1}{16}$ inch of the free end of the foil. When the potential of the upper plate rises above 300 volts, due to accidental connection with the primary, or other circuit, the foil is attracted upward electrostatically, thereby making contact with the lug, and grounding the secondary circuit. This will in most cases blow the fuses in the primary circuit, and cut off the dangerous current.

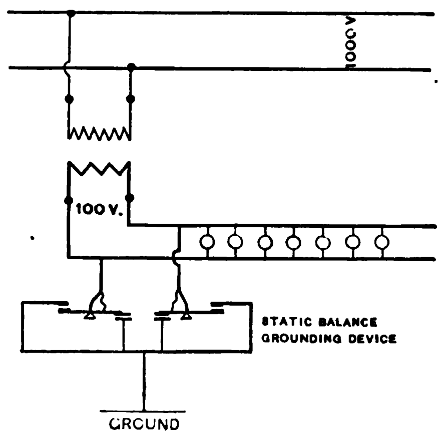


Fig. 139. Automatic Grounding Device.

The film cut-out invented by Professor Elihu Thomson is similar to the Cardew device, the difference being that thin paper or other insulating material is used in place of the air-gap. This is punctured by excessive voltage, and the secondary circuit is

grounded, as is evident from Fig. 138. A similar automatic device is indicated in Fig. 139, the secondary being grounded when an electrostatic balance is caused to act by abnormal potential. It is not necessary that these or other devices should be connected to both wires of the secondary circuit, as in Figs. 138 and 139; one ground connection being sufficient, but two are less likely to fail. Another automatic means of grounding consists of an electromagnet in series with a vacuum tube between the secondary circuit and the ground. When the potential rises above a certain value, it produces current enough through the magnet to cause it to operate a mechanism that grounds the secondary circuit.

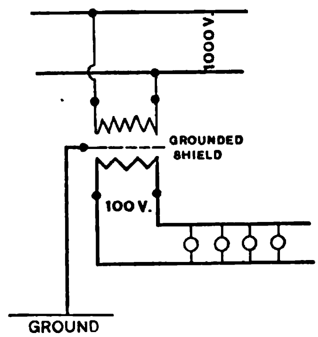


Fig. 140. Transformer Protection.

All of these automatic grounding devices are open to the objections that they do not act instantly, so that the insulation might break down before they operated; besides which they might fail because they depend upon contact points and mechanism.

A grounded metallic shield between primary and secondary coils is another form of protective device due to Professor Thomson. It is simply a covering of sheet metal, placed between the primary and secondary windings in such a manner that it is impossible for current to leap from one to the other without passing through the shield, which naturally leads it away to the ground (Fig. 140), thus protecting the low-tension circuit.

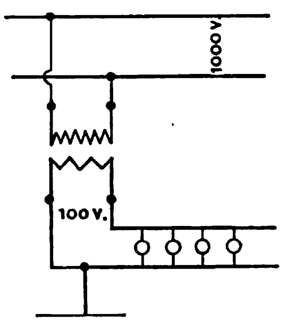


Fig. 141. Grounded Secondary Circuit.

The permanent grounding of the secondary circuit, indicated in Fig. 141, is perhaps the most positive means of protection, but is open to some objections. It was formerly forbidden by insurance rules in this country, but is now permitted. The ground connection should be a very good one, similar to that required for lightning arresters (Vol. I., p. 437), and the wire leading to it should

have a current capacity fully equal to that of those portions of the primary and secondary circuits through which the current might pass to the ground.

The objections to this arrangement are:

1. Insurance authorities have opposed any grounding of strong current electric circuits used inside of buildings, because a single fault would then cause a short circuit or leak, whereas with completely insulated circuits *two simultaneous* faults are required.

2. A permanent ground connection *invites* trouble, since with it a break-down in insulation between primary and secondary is more likely to occur than without it.

3. Certain conditions may arise under which trouble will be aggravated by the ground connection.

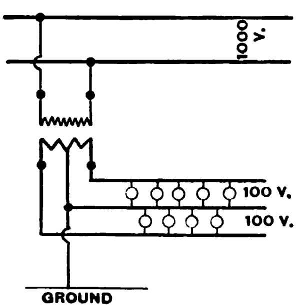


Fig. 142. Secondary Circuit with Neutral Point Grounded.

The first of the above objections is minimized by requiring the ground connection to be made at the neutral point of the secondary circuit. In case the latter is a three-wire system, this is the middle or neutral wire as represented in Fig. 142. With a two-wire secondary circuit the middle point of the secondary coil may be grounded, a connection being brought out for the purpose. By grounding the neutral point instead of one of the outer conductors, the voltage is divided in halves, so that the tendency to break down insulation is reduced in still greater proportion.

The fact that the insulation between primary and secondary is more likely to break down if the latter is grounded, is self-evident; but it may be answered that the consequences are provided for, and the total danger is reduced. There are, however, certain possible conditions which might cause serious trouble on a grounded secondary circuit. For example, an accidental connection between the primary and secondary circuits may allow the primary current to flow through the whole or part of the secondary coil. This will tend to produce an abnormally high voltage in the latter that may rise to several times the ordinary value, so that lamps, sockets, insulation, etc., will be burnt out. In order for this to take place the primary circuit must happen to have a ground connection on

the side opposite to that on which the accidental contact with the secondary exists. It is necessary also that this last-named fault should be on the primary wires before they reach the transformer, otherwise the primary fuses would blow, and cut off the current entirely. In short, this combination of circumstances is not likely to occur, and if it did the danger would be great whether the secondary were grounded or not.

Test wires may be run from the central station and connected to the secondary circuits of the various transformers. This permits the insulation resistance between each of the primary wires and the secondary circuits to be determined at the central station. In fact, a ground detector may be used which would instantly indicate a fault. A single test wire might be used; but it is better to divide the transformers into groups, each of which has its own wire, so that any trouble may be located more readily. These wires may be quite small.

Periodical tests of the insulation of each transformer should be made at least once a year. A small step-up transformer is carried to the places where the tests are to be made. Its secondary voltage should be at least twice the primary voltage of the system, and its current capacity at least four times the charging current that flows during any test. Its primary is connected to the high-voltage lines, and one terminal of its secondary is connected to the primary and the other to the secondary of the house transformer, which must be disconnected previously from both primary and secondary circuits. This pressure is applied for one minute, thus subjecting the insulation between the primary and secondary circuits to twice the working voltage, which is likely to develop any fault. A fuse is put in the circuit to protect it in case the insulation is punctured.

Insulation tests of the primary circuit by means of ground detectors and special measurements are very important on systems using transformers, since any defect in the insulation of the latter will almost certainly lower the general insulation of the primary circuit, giving warning of some trouble. By keeping careful watch on the insulation, and promptly following up any indications, serious consequences may be avoided. This method differs from the preceding one in the fact that no test wires are required.

Transformer Fuse Blocks or Cut-outs. To protect transformers from excessive currents, fuses are inserted in the primary circuit.

The boxes or blocks which contain these fuses may be attached to or combined with the transformer as illustrated in Fig. 128, or they may be entirely separate from it as shown in Fig. 143. In either case the fuse itself is usually inclosed in or carried by a tube or plug of porcelain which is easily inserted and withdrawn through a hole in the box in order to facilitate the inspection or renewal of a fuse. Fuse-blocks are made either double- or single-pole as represented in the two illustrations cited. The presence of a fuse in the primary circuit protects the secondary circuit also, since an abnormal current in the latter causes a corresponding increase in the primary current which will blow the fuse and open the circuit.

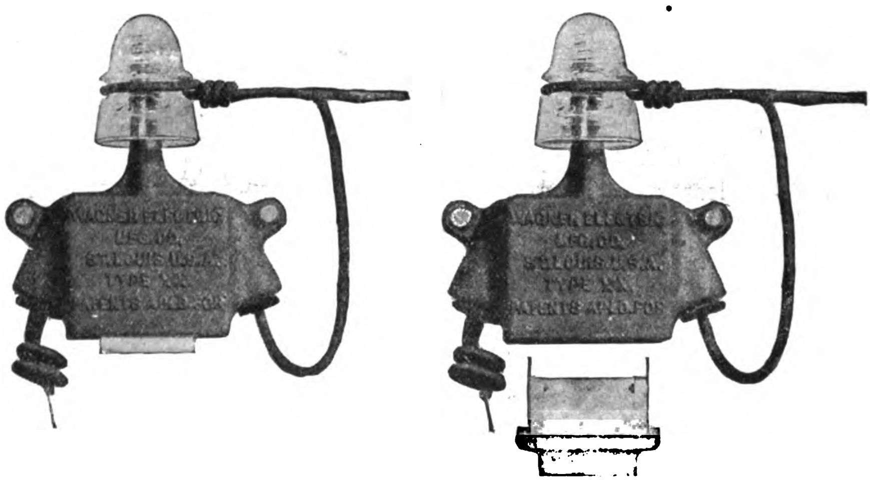


Fig. 143. Transformer Cut-outs.

In most cases the secondary circuit is further protected by fuses inserted in the local or house wiring.

Testing Transformers. For determining *efficiency* various methods have been employed. That used by Professor Ryan * consisted in tracing out by means of instantaneous contacts the curves of primary and secondary *E.M.F.* and of primary current, the secondary current being measured by an ammeter. Having obtained these curves, the power in each circuit was calculated, and the ratio gave the efficiency. This method also has the advantage that the exact form and phase relations of the several waves are brought

* Trans. Amer. Inst. Elec. Eng., Dec., 1889.

out. Mr. W. Mordey * proposed to find the efficiency of a transformer by running it at the given load until a constant temperature is reached as determined by a thermometer or by a resistance test. Direct currents are then passed through the coils of such strength that their heating effect maintains the same constant temperature. It follows that the direct current power ($= I^2R = EI$), which is easily measured by volt- and ampere-meters or by a watt-meter, must be equal to the total losses with the alternating current. Calorimetric methods have been used by Dr. L. Duncan, † the total losses being determined by placing the transformer in a water, oil, or ice calorimeter. Both of these last methods, depending upon heat measurements, are laborious and liable to error.

Volt- and ampere-meters may be employed to measure the pressures and currents in the primary and secondary circuits. If the load is non-inductive and more than one-tenth of full value the product of secondary volts and amperes, divided by the product of primary volts and amperes, is the efficiency. With very light load or with inductive load the current lags behind the *E.M.F.*, and the voltamperes must be multiplied by the power factor ($\cos \phi$) to get the true watts. By means of one of the various three-instrument methods, the true power can be determined; but the simplest plan is to measure the true watts in the primary and in the secondary circuits with *wattmeters.*

Stray power methods are convenient and accurate, the losses being determined individually. The iron losses, which we have seen are constant (page 154), are determined by a wattmeter in the primary circuit when the secondary is open. The copper losses may be calculated for any load by (69) if the primary and secondary currents as well as resistances are known or can be measured, which is usually an easy matter. Since the efficiency is always found for a definite load, the secondary current is fixed by that fact. The primary current I' is

$$I' = \frac{I''}{k} + I_1 \tag{76}$$

in which I'' is the secondary current, k the ratio of transformation, and I_1 the exciting current which flows with open secondary. If

* Jour. Inst. Elec. Eng., London, vol. XVIII. p. 608.

† Electrical World, vol. IX. p. 188.

I_1 is assumed to be 3 per cent of $I'' \div k$ the error in the efficiency will be very slight. Having determined the iron and copper losses the efficiency is equal to the secondary watts divided by the secondary watts plus the losses as given by (72).

Potential Transformers are used to furnish current for voltmeters or wattmeters. They are small transformers (Fig. 144), usually mounted on the switchboard, their function being to convert high voltages to lower values that are more convenient and safer to measure. With a definite ratio of transformation, a volt- or wattmeter supplied from the low-voltage secondary circuit, can be calibrated to indicate the original or primary voltage. If the currents consumed produce a certain percentage of drop in the secondary voltage a corresponding error is introduced, unless the instrument is specially calibrated to allow for this. A simpler plan is to use a transformer having sufficient capacity so that the drop is insignificant. One should not connect additional instruments or pilot lamps to a potential transformer until it has been ascertained that they do not cause an objectionable fall in secondary voltage.

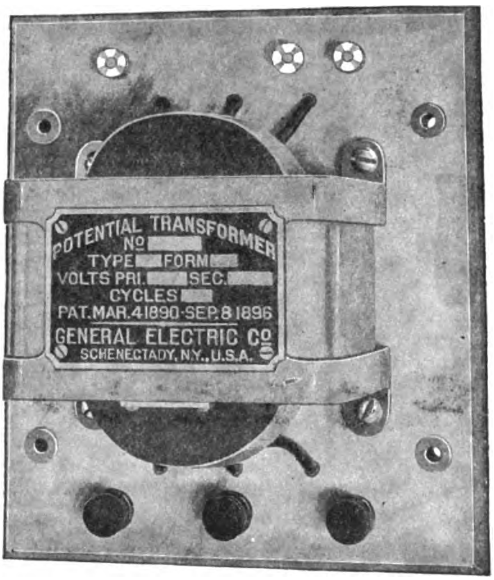


Fig. 144. Potential Transformer.

Auto-Transformers. In these devices the primary and secondary currents both flow in a single winding. The circuits of one form of auto-transformer are represented in Fig. 145, A B being a coil of insulated wire wound upon an iron core as in an ordinary transformer. When the coil AB is supplied with alternating current from the primary circuit on the left, differences of potential are established between the various parts of the coil. If connections are made to it at the points C and D, which divide it into three equal parts, the potential difference between D and E will

be one-third of the total voltage applied at *A* and *B*, and between *C E* it will be two-thirds of that value. Assuming, for example, that 300 volts are supplied at *A* and *B*, then 100 volts may be tapped off from *D* and *E* and 200 volts between *C* and *E*.

These might be used in almost exactly the same way as the common types of transformer with separate primary and secondary circuits, since a certain number of watts at one voltage may be converted into a nearly equal number of watts at another voltage.

There is an objection, however, to auto-transformers, arising from the fact that the secondary is connected directly to the primary circuit, as at *B* and *E* in Fig. 145. Although the actual voltage between the secondary wires may not be high, nevertheless conditions may arise that will make the secondary circuits very dangerous. For example, an accidental ground anywhere on the primary conductor *A* will subject to the full primary voltage a person who is connected to the earth and happens to touch the secondary wire *E*. It is practically the same as if the primary current breaks through to the secondary circuit in an ordinary transformer, and we have seen in Figs. 138 to 142 what precautions are taken to make this danger as small as possible. On this account auto-transformers are not suitable for general use on high-tension systems. They are employed chiefly for series circuits in electric lighting, as described under that head in the next chapter. They are used also in place of dead resistance for starting alternating current motors. It is evident that they may be applied as compensators to subdivide the voltage in three- and five-wire systems instead of the machines described on page 79.

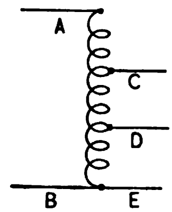


Fig. 145.
Auto-Transformer.

The action of an auto-transformer is similar to that of the ordinary transformer. In either case the primary current sets up an alternating magnetic flux which induces an *E.M.F.* in each turn of winding. In an auto-transformer there is only one winding; but if any two points, as *D* and *E* in Fig. 145, are connected to a suitable circuit, a current will flow through it. This tends to produce a demagnetizing effect similar to that due to the secondary current of the common transformer; hence the primary current increases, in order to maintain the same magnetization, and automatically adjusts itself to supply the energy drawn in the secondary circuit.

Reactive and choke coils, which are somewhat similar in construction and action, will be described as means of regulation in the next chapter.

Standard Types of Transformers. The following table gives data concerning standard commercial transformers of from .6 to 50 k.w. capacity. It will be noted that the 125 cycle type has less core loss, and higher efficiency, but poorer regulation, than the 60 cycle type; the differences, however, are not very great.

GENERAL ELECTRIC TYPE H OIL TRANSFORMERS.

ADAPTED FOR USE ON 50 TO 140 CYCLE CIRCUITS.

Data Based on 1040 or 2080 Volts Primary and 60 Cycles (Column A), or 125 Cycles (Column B).

Watts Capacity.	Core Loss, Watts.		Full Load Copper Loss, Watts.	Regulation, Per Cent.		Efficiency. Full Load.		Efficiency. Three-Quarters Load.		Efficiency. One-Half Load.		Efficiency. One-Quarter Load.		Weight in Lbs.
	A	B		A	B	A	B	A	B	A	B	A	B	
600	25	20	16.7	2.93	3.50	93.5	94.2	92.9	93.8	91.1	92.5	85.2	87.7	70
1,000	32	25	27.4	2.80	2.87	94.4	95.0	94.0	94.9	92.8	93.0	88.1	90.4	95
1,500	38	30	37.5	2.63	2.90	95.2	95.7	95.0	95.6	94.0	95.0	90.3	92.1	125
2,000	45	35	50.0	2.58	2.80	95.5	95.9	95.4	96.0	94.5	95.5	91.2	92.9	155
2,500	50	39	54.0	2.23	2.50	96.0	96.4	95.9	96.4	95.1	96.0	92.1	93.6	195
3,000	55	42	62.0	2.13	2.40	96.2	96.7	96.1	96.7	95.5	96.3	92.7	94.2	220
4,000	63	49	85.0	2.19	2.40	96.4	96.7	96.4	96.8	95.9	96.6	93.6	94.8	270
5,000	70	51	105.0	2.17	2.40	96.6	96.9	96.6	97.0	96.2	96.9	94.2	95.3	350
7,500	110	85	147.0	2.10	2.20	96.7	97.0	96.6	97.1	96.2	96.9	94.0	95.2	470
10,000	140	108	177.0	1.90	2.00	96.9	97.2	96.9	97.3	96.4	97.0	94.3	95.4	535
15,000	175	135	272.0	1.90	1.95	97.1	97.4	97.1	97.5	96.8	97.3	95.1	96.1	850
20,000	190	147	356.0	1.94	2.10	97.3	97.5	97.4	97.7	97.2	97.6	95.9	96.7	995
25,000	220	170	460.0	1.98	2.10	97.3	97.6	97.5	97.8	97.3	97.7	96.1	96.9	1210
30,000	250	193	495.0	1.81	2.00	97.5	97.7	97.7	97.9	97.5	97.8	96.3	97.1	1500
40,000	390	300	590.0	1.65	1.90	97.6	97.8	97.6	97.9	97.4	97.8	95.9	96.7	1780
50,000	460	354	690.0	1.48	1.70	97.7	97.9	97.7	98.0	97.5	97.9	96.1	96.9	1900

Temperature rise not exceeding 45° C. for A and 40° C. for B in 8 hours full load.

Temperature determined by increase of resistance method.

For comparison with data based on 1000 or 2000 volts primary, deduct 7% from the above core loss and add 0.1 to the per cent regulation.

The above transformers are suitable for operation on circuits having voltage within 10% above or below the rating.

Polyphase Transformers. Exactly the same types of transformers as those used for single-phase currents may be employed with two- and three-phase currents, each phase or branch having its own transformer or set of transformers. It is possible, also, to construct special polyphase transformers in which the magnetic circuits are combined in a manner analogous to that in which the

electric circuits are interconnected, as explained with reference to Fig. 115. In this way a certain saving in the material of the iron core is effected; but they are more complicated in construction than ordinary transformers, and are seldom used in this country. A description of them may be found in Jackson's *Alternating Currents*, page 683. The arrangement and operation of transformers in connection with polyphase systems will be described in the next chapter.

For further information regarding the theory, construction, and operation of transformers reference may be made to the following works:

The Alternate Current Transformer, by J. A. Fleming, new edition, 2 vols. N. Y. and London, 1896.

Alternating Current Phenomena, by C. P. Steinmetz, N. Y., 1900.

Alternating Currents, by D. C. and J. P. Jackson, N. Y. and London, 1896.

The Principles of the Transformer, by F. Bedell, N. Y. and London, 1896.

CHAPTER X.

ALTERNATING CURRENT SYSTEMS OF DISTRIBUTION.

THE facility with which alternating currents may be transformed from one voltage to another gives possibilities of variation in systems of distribution that are greater than with direct currents. Adding to this the transformation from two- to three-phase, and from alternating to direct currents, or vice versa, by rectifiers and rotary converters, and the opportunity for elaboration becomes almost unlimited. There has been a tendency to yield to this temptation, and go too far in the complication of circuits and apparatus. Certain systems have become more or less standardized and generally accepted, but alternating current practice is still far less definite than direct current work. The more important methods will be classified and described in the present chapter.

Alternating Current Series Systems. — Series circuits corresponding to the direct current arrangements shown in Chapter II. may be operated by alternating currents. The principal systems that have been used are —

1. Simple series circuit with constant current alternator.
2. Series circuits supplied by constant current transformers.
3. Parallel-series circuits.

Several forms of constant current alternators have been introduced, analogous to the well-known Brush and Thomson-Houston series arc dynamos, the principal example being the Stanley machine made by the Westinghouse Company. No regulating device is required to keep the current constant; but armature reaction and self-induction are purposely exaggerated in the design, so that the current does not increase very much, even when the machine is short-circuited. The same is true to a certain extent of a constant direct current dynamo, but self-induction has a much greater effect with alternating currents. On the other hand, the voltage of a

constant current alternator rises very high if the circuit is opened, since it is entirely relieved of armature reaction and inductance drop. This is likely to break down insulation unless it is prevented by providing a film cut-out similar to that shown on page 25, or some other device connected to the terminals of the machines, so that it will short-circuit the latter if the voltage becomes too great. Such machines have no advantage over constant direct current dynamos, except that the main current is generated without a commutator; but they require some source of direct current for field excitation. Furthermore, there are many examples of the direct current type that are very successful, hence they are generally adopted for arc-lighting on a simple series circuit, the direct current lamp being preferred when other considerations are equal.

Constant current transformers have been illustrated in Figs.

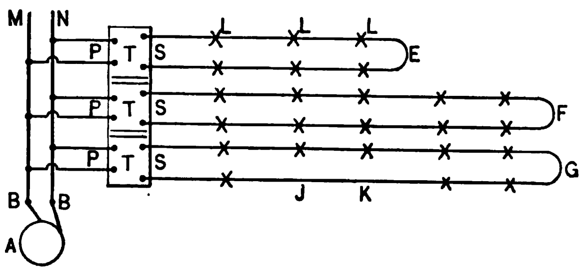


Fig. 146. Constant Current Transformer System.

135, 136, and 137, and their operation described. They are not used on a true series system, since their primaries *P* are supplied in parallel at constant potential, as represented in Fig. 146, the secondary circuits *S* only being arranged in series fashion, and carrying constant currents which feed the lamps L. The advantage of this method is the fact that a large number of lights can be operated from the same source of current. For example, each of the circuits in *E,F,G,* Fig. 146, may have as many lamps as an entire dynamo in the direct current series system; so that one large alternator of 1000 k.w. capacity can supply about 2000 lights; whereas it would require 16 to 20 direct current machines, since the number of lamps that can be fed by a single dynamo is usually limited to 100 or 125. In simplicity and in economy of operation the single large alternator would have considerable advantage. The transformers *T,T,T,* may be of different sizes, if

desired, being used to supply a larger or smaller number of lights. Lamps may also be cut out of circuit, as at *J* and *K*, the current being kept constant by the transformer in each case; but the latter may be designed or adjusted to maintain in one circuit a different value from that in the others. The primary circuits *P* are fed by the mains *MN*, with constant voltage from the alternator *A*; hence the current in each primary is nearly proportional to the watts in the secondary. In other words, it increases as lamps are added in series. On the other hand, the current is constant in each secondary circuit, and the voltage automatically rises as the number of lamps is increased. Thus we have the interesting case of a constant potential primary and a constant current secondary circuit. This is made possible by the fact that the flux through the secondary coils varies with the load, whereas it is practically unchanged in the ordinary transformer. Hence the core loss is not a constant in the former, but the copper loss is always the same in the secondary coil, and increases in the primary circuit as the square of the load. The last fact is true of a constant potential transformer, but the first two do not apply to it.

Parallel-series systems are often operated by alternating currents, being analogous to the direct current circuits shown on page 26. Like the latter, they are used chiefly for street-lighting with series incandescent lamps. The general arrangement is similar to that represented in Fig. 9, one source of current being used to feed several circuits in parallel. Hence all are supplied with the same voltage, introducing difficulties when lamps burn out, or when it is desired to run different numbers of lamps on the various circuits. One plan consists in switching in extra or "relief" lamps *L*, as is done with the direct current system described on page 26. But the alternating current has an advantage over the latter in this respect, as it may be regulated by reactive coils, or auto-transformers (Fig. 145), which are more efficient and convenient than resistance coils or lamps. Several such methods have been used, in one of which variable reactive coils are placed in series with each circuit, and any reduction in the number of lamps is compensated by increasing the reactance drop in the coil. In another arrangement each lamp *L* is shunted with a reactive coil C, as illustrated in Fig. 147. These coils consume very little real power, but they have a certain potential difference across their

terminals, thus feeding the lamps. When one of the latter burns out the continuity of the circuit is maintained, the current flowing through the coil, which also consumes about the same voltage as before. But as this last condition is only approximately fulfilled, it is necessary to have additional reactive coils *R* in each circuit to regulate the current.

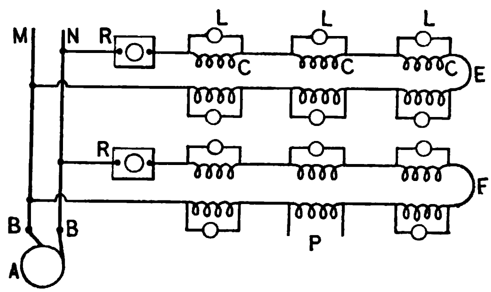


Fig. 147. Alternating Current Series System.

The so-called *CR* regulator, made by the General Electric Company, is another means of operating series incandescent lamps. It consists of an auto-transformer, the connections of which are shown in Fig. 148. The primary coil *AFB*, and the coils *BE* and *CD*, are all wound upon the same iron core. When a plug is inserted in the contacts at *R*, and the switch arms *H* and *G* are in the position indicated, the voltage of the supply circuit from the switchboard

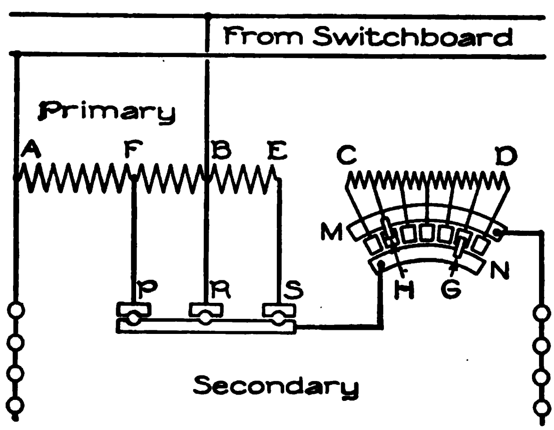


Fig. 148. Regulator for Alternating Current Series Systems.

is *decreased* by the opposing *E.M.F.* produced in the portion of the coil *CD* included between the arms *H* and *G*. If the position of the latter is reversed, then the primary voltage is increased by the same amount. Thus the whole or part of the

coil CD may be made to raise or lower the primary *E.M.F.* by moving the arms GH. Transferring the plug from R to S increases the primary *E.M.F.* by the voltage produced in the coil BE; and on changing the plug to P, the primary *E.M.F.* is diminished by that due to the coil FB. This secures a wide range of regulation; for example, the primary AB is wound for 2200 volts, FB and BE being each wound for 430, while CD produces 230 volts in steps of 23. With a plug at P, the secondary gives $2200 - 430 = 1770$ volts, with the arms G and H in the middle; and by moving the latter the voltage may be varied from 1540 to 2000. Changing the plug connection to R, the regulation is from 1970 to 2430, and putting it in S, the range is from 2400 to 2860 volts, the total variation being 1540 to 2860. These regulators are also wound for 1100 volts, giving a range in secondary voltage from 440 to 1760. The secondary current is either 3.5 or 5.5 amperes, lamps designed for this current being connected in series, but only the two ends of the circuit are shown in Fig. 148. Several circuits, each with its own regulator, are connected to the same source of alternating current in a manner similar to that represented in Fig. 146. Each circuit is provided with an ammeter, and the attendant regulates the current by moving the switch arms GH, when it is too high or too low. The lamps take about 1 volt per candle-power at 3.5 amperes, and are arranged with automatic cut-outs, which short-circuit them if they break, as explained on page 25.

Alternating Current Parallel Systems. The simple arrangement of lamps in parallel on a two-wire circuit may be supplied by an alternator without transformers, being analogous to the ordinary direct current system represented on page 28. This method, however, is rarely used for electric lighting alone, since the direct current has generally been adopted in such cases, including the majority of isolated or other plants in which the distances are not great. For the operation of motors, polyphase parallel systems are often used with or without transformation of voltage; and lamps are supplied from the same circuits or generators, but they are not intended primarily for electric lighting. The single-phase current is not well adapted to the running of motors for general purposes, this being the principal objection to it. It is only when the voltage is to be transformed up or down that the single-phase has any

special advantage over the direct current system, hence it is seldom used without transformers. But there is nothing to prevent the installation of two- or three-wire systems similar to those illustrated on pages 28 and 70, the direct current dynamos being replaced by alternators of equivalent voltage and current capacity. In fact, such plants have been installed in a few instances.

Single-phase parallel systems with transformers. This is the most common method of distribution with alternating currents. One alternator *A* (Fig. 149), or two or more alternators *A* and *B* working in parallel, supply current to the bus-bars *UV*, from which the lines *MN* and *RS* convey current to the primary circuits *P* of the various transformers *T*. The lamps *L* are connected in parallel to the secondary circuits *S* of the transformers. The latter operate at approximately constant potential in both primary and

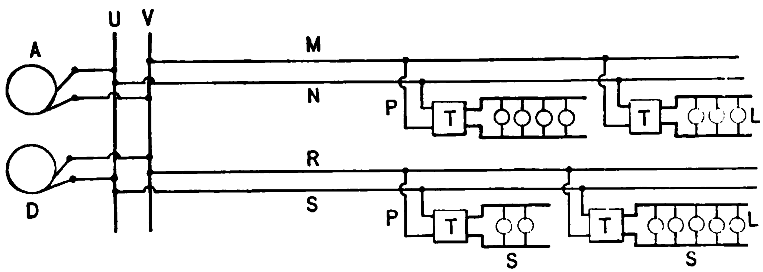
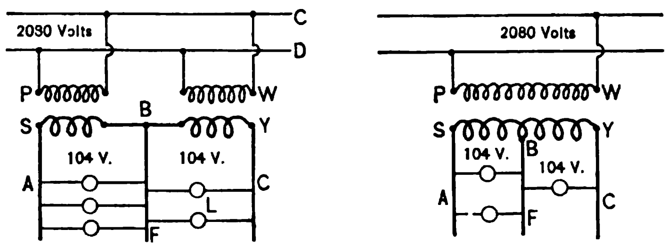


Fig. 149. Constant Potential Transformer System.

secondary circuits, being of the ordinary type that has been fully discussed in the preceding chapter. In most cases the alternators generate about 1100 or 2200 volts, which is carried with a loss of about 10 per cent by the conductors *MN*, so that the primary coils of the transformers *T* receive about 1,000 or 2,000 volts, which is transformed down to about 100 volts for supplying the lamps *L* on the secondary circuits. Formerly a secondary voltage of 52 was generally employed, but at present 104 volts has become the standard in alternating current practice. This change reduces the weight of copper in the secondary wiring to one-quarter with the same percentage of drop. There is a tendency to economize still further in the secondary conductors by adopting lamps of 220 or 208 volts, or by using the three-wire system as described in the following paragraph.

Three-wire Alternating Current Systems. As already stated,

two- or three-wire parallel circuits may be supplied by single-phase generators without transformers, but they are seldom used. The two- and three-phase systems may also be operated with three wires, and will be described later. The system here referred to corresponds to the ordinary direct current three-wire circuits set forth on page 70, except that it is supplied from the secondary coils of transformers. When the alternating current was first introduced for electric lighting the secondary circuits and lamps were generally operated at 52 volts, a transformer being placed in or near each house to be lighted. But it was found that the lower efficiency and greater core-loss of a number of small transformers gave results far less economical than those obtained by the use of fewer transformers of larger size. This naturally requires that the average lengths of the secondary circuits should be increased; and



Figs. 150 and 151. Three-wire Single-phase Systems.

in order to avoid excessive cost in the latter, 104-volt lamps have become the standard in alternating current installations. The next step in this direction is the adoption of the three-wire system for the secondary circuits. This is easily arranged either by employing two transformers as represented in Fig. 150, or by using a transformer with two equal secondary coils as in Fig. 151. In both cases the primary is an ordinary two-wire circuit, all the primary coils being connected in parallel; but each pair of secondary coils are put in series, the neutral wire *F* being led from the intermediate point *B*. The *unlike* terminals must be connected at *B* in order to give double voltage between the outside wires *A* and *C*. If the like terminals are united at *B* the two sides will be in parallel, and the middle wire *F* must carry the sum of, instead of the difference between, the currents on the outer conductors, as explained on page 82.

A two- or three-wire network of conductors, similar to the direct current systems described in Chapter VI., is often adopted for alternating current distribution. A transformer *T*, or a bank of transformers, is placed at each feeding-point, the primary coils being supplied from the station generators *A B* by the high-voltage conductors *E F G H*, and the secondary coils being connected to the low-tension mains composing the network *NM*. These transformers are located in sub-stations or in manholes in the street. The lamps *LL* are fed from the network as indicated in Fig. 152. In this case a two-wire network is shown; but a three-wire system similar to that represented in Fig. 74 is also used in many places, the transformers being connected in the manner shown in Figs. 150 and 151.

Regulation of Constant-Potential Alternating Current Systems. Nearly all of the methods of regulating the voltage of direct current systems described on pages 51 to 69 are applicable to alternating current circuits. For example, the potential of an alternator may be controlled by varying its field current, using the ordinary rheostat operated by hand. In this way the voltage of the generator may be kept constant or may be increased a certain amount with rising load to make up for the drop in lines and transformers. This drop is greater for alternating than for direct currents on account of reactance, and the falling off in potential of alternators is also larger at full load than with dynamos.

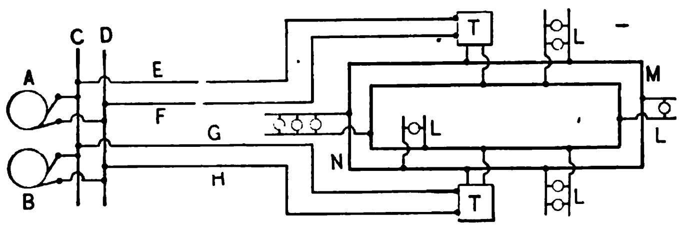


Fig. 152. Network supplied by Transformers.

Composite Wound Alternators. To make an alternator automatically maintain a constant, or a rising voltage with increase of load, it is provided with *composite* winding analogous to the compound winding of direct current machines.

In order that a generator may be self-regulating, the current which it produces is caused to act upon the field-magnets in order

to increase their strength in proportion to the current generated. Since an alternating current cannot be used directly for exciting the field-magnets it is necessary to rectify it for the purpose. One method is indicated in Fig. 153, the coils *CC* being the ordinary field winding supplied by the separate exciter *E*, and producing most of the magnetization. The composite coils *DD* are also wound upon the field-cores, and are fed through the rectifying commutator *R*, which is mounted upon the same shaft as the armature *AA*, but to avoid confusion is represented on one side in the diagram. The commutator *R* has as many segments as there are poles, alternate segments being connected to one terminal *T* of the armature winding, and the intermediate segments being connected to one of the lines *M* by the wire *W*, and brush

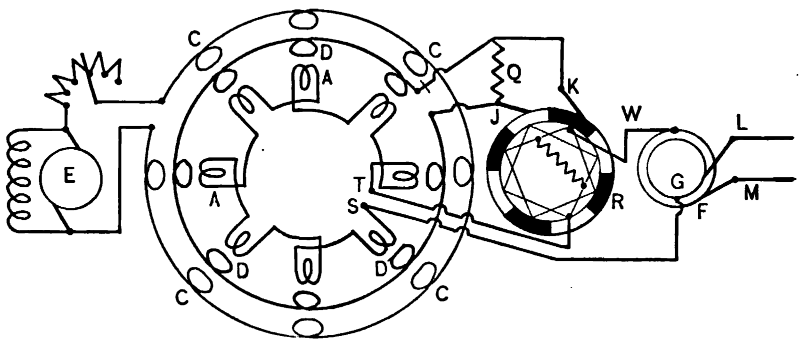


Fig. 153. Composite-wound Alternator.

on the collecting-ring at *F*. The other terminal *S* of the armature winding is connected to the second collecting-ring *G*. The collecting-rings *FG* are also mounted upon the shaft in the usual manner. With this arrangement, the connections of the composite coils *D* are reversed at the brushes *J* and *K* each time that the armature current reverses, so that a unidirectional flow is established through these coils. This tends to augment the magnetization of the field as the load increases, the effect being the same as that of compound winding. It is necessary that the brushes *J* and *K* should be set carefully, so that each passes from one segment to the next at the same instant that the current reverses. In this way sparking is avoided since the current is zero at that moment. A shunt shown inside of the commutator *R* in the diagram, and moving with it, is sometimes used when it is desired to rectify

only a portion of the current. A stationary shunt *Q* is generally employed to regulate the current in the coils *DD*, thus giving a means of adjusting the amount of compounding.

In most cases the current produced by an alternator is of high potential, so that it is not desirable to introduce a commutator in the main circuit or to pass this current through the field-coils. To avoid these objections, the main current is carried through the primary coil of a small transformer, the secondary of which is connected to the segments of the commutator *R*, and is wound to give a low voltage. The latter is therefore directly proportional to the main current, and produces through the brushes *J* and *K* a magnetizing current in the composite coils *DD* that increases with the load. This transformer is usually placed inside of the armature. Instead of putting a composite coil *D* on each field core, as represented in Fig. 153, they are sometimes concentrated upon one or two of the field cores. If the two halves of the armature winding are in parallel, composite coils must be put on at least two poles; and these must have symmetrical positions, otherwise the *E.M.F.* in the two armature circuits will be unbalanced.

The above-described forms of composite-wound alternators do not regulate properly for inductive as well as non-inductive loads, but the General Electric Company build *compensated field alternators* designed to adjust automatically the voltage for all variations in load or lag. This machine is described in the *American Electrician*, Nov., 1899, and *Elec. Review* (N.Y.), May 23, 1900.

The automatic constant-potential regulator described on page 57 is used for alternating as well as direct current systems. The arrangement employed for the former is fully illustrated and described in the *American Electrician* of October, 1899, p. 488. Another arrangement of this kind, made by Ganz & Company of Buda-Pesth, is described in the work on *Alternating Currents* by D. C. and J. P. Jackson, page 313. It consists essentially of a solenoid connected as a high-resistance shunt to the main circuit, and controlling a number of contact points dipping in mercury, thus varying the resistance in the field circuit.

Feeder Regulation. The various methods of regulating direct current feeders described on pages 61 to 69 are applicable with slight modification to alternating current distribution. It is evident, for example, that the introduction of non-inductive resistance

in any circuit will produce a drop in voltage equal to the product of the current and resistance. Hence, the regulation of feeders by means of rheostats, as described on page 64, is practically the same for alternating as for direct currents. In addition to this the effect of self-induction may be utilized to produce a drop in voltage if desired. On page 125 it was shown that the drop due to inductance alone is $2\pi fLI$ and that due to resistance and inductance combined is $I\sqrt{R^2 + (2\pi fL)^2}$. In practice *self-induction coils* are often employed to control alternating currents, and they possess the advantages over resistance coils that they are more compact, and consume much less actual energy for the same drop, but they cause the current to lag. Various names are applied to them, such as reactance coils, impedance coils, and choke coils. By subdividing them, and leading out connections to contact points, the effect may be varied as in the case of an ordinary rheostat.

Feeder Regulation by Variable Ratio Transformers is a very convenient method in alternating current distribution. They take the place of the "boosters" (page 67) used in direct current systems. It would be possible to vary the potential of a feeder by means of an auxiliary alternating current machine put in series with it, and acting either as a generator or motor to raise or lower the voltage. But a transformer being simpler, cheaper, and more easily taken care of, is generally used to accomplish the same results. There are several such devices in common use, a prominent example being the Stillwell Regulator, made by the Westinghouse Company, and represented in Fig. 154. It consists of a primary coil, which is connected in shunt, and a secondary coil in series with the main circuit. By means of a movable switch arm, more or less of the secondary winding may be introduced into the circuit, thus "boosting" by a corresponding amount the voltage of the generator. A switch is provided to reverse the connections of the primary coil, so that the secondary potential may be added to or subtracted from that of the alternator, thus doubling the range of regulation. Assuming that the secondary coil is wound for 100 amperes and 100 volts, and that the alternator generates 2100 volts, the circuit will be supplied at 2200 volts, when all of the secondary winding is inserted so as to raise the pressure the full amount. By moving the switch arm to the left, part of the secondary is cut out, and the voltage is reduced until it becomes 2100, when the arm is at zero.

On reversing the primary coil by the lower switch, and then moving the arm of the upper switch to the right, the opposing *E.M.F.* set up in the secondary winding reduces the pressure of the feeder, until finally it becomes 2000 volts. In this way any value between 2000 and 2200 volts may be obtained. When the secondary is adding 100 volts to the generator's potential, it is producing 10,000

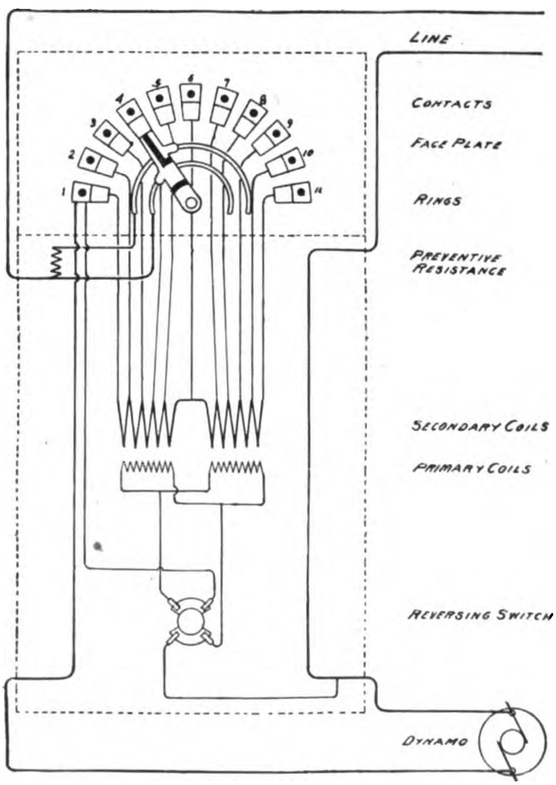


Fig. 154. Internal Connections of Stillwell Regulator.

watts with a current of 100 amperes. Under those circumstances it will draw 2100 volts, and about 5 amperes, or about 10,500 watts, from the alternator; the difference being the various losses in the transformer, which would have an efficiency of about 95 per cent. If the primary is reversed in order to reduce the voltage, about 95 per cent of the energy is returned to the circuit. Hence the actual loss is small in any case, being only about $\frac{1}{20} \times \frac{1}{20} = \frac{1}{400}$,

or ¼% at maximum or minimum voltage, and less than that at intermediate values. Regulators are required when two or more feeders are to be operated at different potentials. If there is only one circuit, or if all the feeders are supplied with the same voltage, the regulation may be accomplished by varying the field of the alternators by means of rheostats. But when one feeder demands a different pressure from the others, then each should be provided with its own regulator, allowing independent control according to the load, distance, and other conditions.

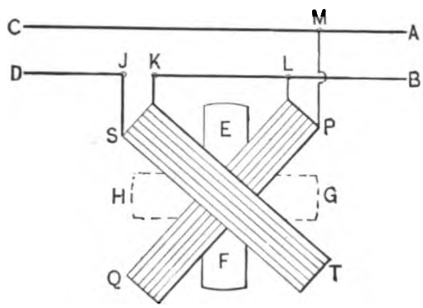


Fig. 155. Principle of Feeder Regulator.

Another type of feeder regulator made by the General Electric Company is represented in Fig. 156. The principle of its action is shown diagrammatically in Fig. 155, PQ being the primary coil of many turns of fine wire connected across the main conductors AB, coming from the alternator, and ST being the secondary coil of a few turns of heavy wire connected in series with one of the main conductors at JK. A laminated iron core EF is mounted within the primary and secondary coils, and is capable of being turned into the position GH, indicated by dotted lines. When the core is vertical, the magnetic lines produced in it by the primary coil PQ, set up a certain $E.M.F.$ in the secondary coil ST, and we assume that this aids the $E.M.F.$ of the generator. If, now, the core be turned


Fig. 156. Feeder Regulator with Cover Removed.

to the position *GH*, then the direction of the lines of force are reversed with respect to the secondary coil, so that an opposing *E.M.F.* will be produced. Thus, by turning the core, the potential difference between the line wires *C* and *D* may be raised above or reduced below that of the generator conductors *A* and *B*. This device has the advantage of being free from sliding contacts, the regulation being obtained by shifting or reversing the flux, and the variation is perfectly gradual — not in abrupt steps. The actual construction is illustrated in Fig. 156, both coils with their terminals being clearly seen. A ring of laminated iron (not shown in either cut) surrounds the coils and core, in order to improve the magnetic circuit; and all the parts are inclosed in a cast-iron case, which may be filled with oil for cooling and insulating purposes. The core is turned by means of the hand wheel shown in Fig. 156. These regulators may be used also for dimming lights in a theater, as controllers for series lighting instead of the arrangement shown in Fig. 148, or to adjust the voltage on the branches of an unbalanced polyphase, or three-wire single-phase system.

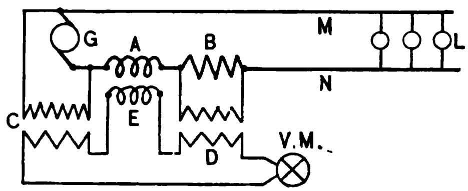


Fig. 157. Mershon Compensator for Voltmeter.

Compensators for Voltmeters. In order to determine the voltage at the outer end of a feeder, it is necessary to run special "pressure wires" from the station to the given point, or to use a compensated voltmeter, as explained on page 64. With alternating currents, the latter method is much more difficult to apply than with direct currents, because the compensator must allow for both ohmic and inductive drops, and must be correct, whether the current lags or leads with respect to the *E.M.F.* These conditions are fulfilled by the *Mershon compensator,* made by the Westinghouse Company, and represented in Fig. 157. The generator *G* supplies the lamps *L*, through the feeders *MN*. The ordinary potential transformer *C* is used to reduce the pressure for the voltmeter *VM*; and an inductance *A*, as well as an ohmic resistance *B*, are inserted in series with one main conductor. The drop due to *A* and *B* is introduced into the voltmeter circuit by two small transformers *E* and *D*, the iron core upon which the inductance *A* is

wound being used as the core of the transformer E, of which the coil A is the primary. With this arrangement C gives to the voltmeter a pressure proportional to that of the generator; while E introduces into the voltmeter circuit an opposing $E.M.F.$ proportional to and in step with the inductive drop on the line, and D produces another opposing $E.M.F.$ proportional to the ohmic drop on the line. The result is that the voltmeter indicates the voltage at the distant end of the line or feeder. The plan here shown is commonly employed, but various modifications are possible.

Polyphase Systems. The principles of two- and three-phase circuits have been shown in Figs. 110 to 121, and will enable us now to consider their application in systems of distribution. As already stated, a two-phase circuit is practically equivalent to two single-phase circuits, and each may be considered separately. In fact, in most cases they are used separately for electric lighting, as represented in Fig. 111; and even when the two circuits have a common return conductor in order to save one of the four wires (Fig. 112), the conditions are practically the same as for single-phase distribution, except that the common conductor C carries a current 1.41 times greater than that in B or E, as explained in connection with Fig. 113.

For isolated plants or central stations supplying polyphase current at moderate distances transformers are not required; and the lamps, motors, etc., may be connected directly to the circuits, as indicated in Figs. 111, 112, 115, and 117. In such cases the pressure may be about 110 or 220 volts, which is suitable for incandescent lighting and for constant potential arc lighting, the lamps being connected singly or two in series. Either the two- or three-phase systems are often adopted where the operation of motors is an important part of the service. For example, in many cotton mills the looms and other machinery are run by polyphase induction motors, and it is convenient to feed the lamps from the same generators. It is generally preferable, however, to employ separate circuits for lighting and power in order to avoid the objectionable effect of the latter upon the former due to the sudden and large increase in current occurring when motors are started. This difficulty is almost always met with if motors and incandescent lamps are supplied by the same circuits; but it is usually more serious with alternating than with direct currents, because most types of

alternating current motors require a heavy current, usually lagging considerably, when starting. This not only causes a large drop on the line, but also reacts injuriously upon the regulation of transformers and generators, their voltage falling much more than with an equal non-inductive load.

When the distances become considerable, that is, more than two or three miles, it is customary to employ pressures of about 1000 or 2000 volts or higher, to economize in the conductors, and for long distance transmission of 50 miles or more 30,000 to 40,000 volts are employed. In any of these cases, transformers are required to reduce the high voltage for transmission to low voltage for actual use in the lamps. Special polyphase transformers may be employed; but in most cases, especially in America, ordinary types the same as those designed for single-phase systems are adopted for polyphase work.

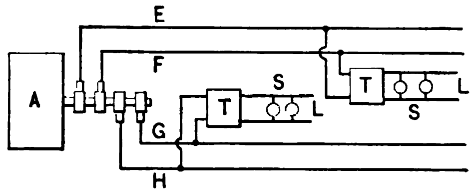


Fig. 158. Two-phase Circuit with Transformers.

For two-phase circuits the connections are very simple, as shown in Fig. 158, being precisely similar to the single-phase arrangement. The primary of each transformer T is connected to the main conductors EF of one phase or to GH of the other phase, the lamps L being fed by the secondary circuits S. The generator A is an ordinary two-phase alternator. Any number of transformers may be supplied from either or both circuits EF and GH up to their full capacity, there being no necessity for preserving a balance between them. If a two-phase motor is to be operated, it is connected to the secondaries of two transformers, one of which has its primary supplied from the circuit of one phase, and the other having its primary supplied by the circuit of the other phase, thus producing a two-phase current in the motor. If a single return conductor is used for both circuits, the transformers are connected as represented in Fig. 159, the wire F

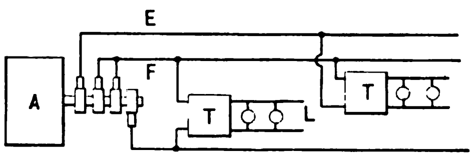


Fig. 159. Two-phase Circuit with Transformers.

being common to both circuits. The secondary circuits of transformers on polyphase systems may be arranged for three-wire distribution in the same manner as the single-phase circuits in Figs. 150 and 151. All that is necessary is to use two transformers in series or to subdivide the secondary of each transformer. It is evident also that two-wire or three-wire networks similar to that illustrated in Fig. 152 may be supplied with polyphase currents.

On three-phase circuits transformers may be connected either in Y or in Δ fashion as indicated in Figs. 160 and 161 respectively. In the former case, three transformers have one terminal of their primary circuits brought to a common or neutral point *P*, or a fourth conductor may be provided, as in Fig. 115, in order to connect these neutral points together.

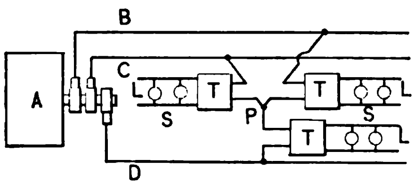


Fig. 160. Three-phase Y Circuit with Transformers.

With the Δ arrangement (Fig. 161) the primary of each transformer is connected between two of the three main wires, and the loads on the three branches must be closely balanced, otherwise their voltages will not be equal. The same is true of the three-wire Y circuit; but the addition of a fourth or neutral conductor renders it unnecessary to maintain a balance provided the armature of the generator has a Y winding, the neutral point of which is connected by means of this fourth wire to one primary terminal of every transformer. This last arrangement is the best one for supplying lamps by three-phase currents, but is not needed for motors, since the latter are connected to all three conductors, and draw current from them equally.

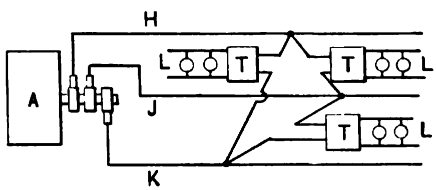
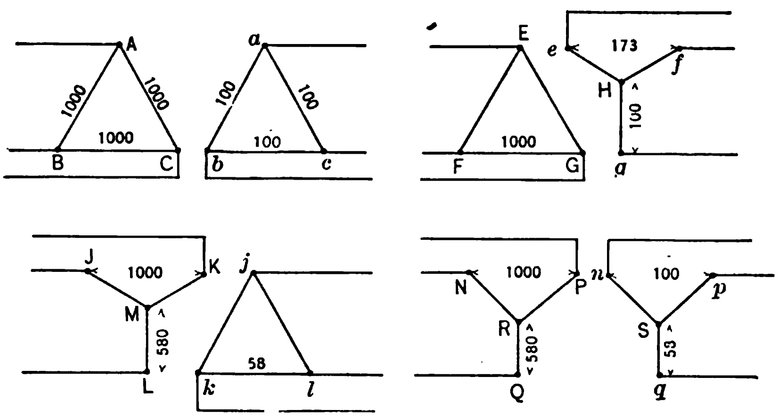


Fig. 161. Three-phase Δ Circuit with Transformers.

In the three-phase systems already shown (Figs. 160 and 161) the secondary circuits are used separately, but if desired they may be connected according to the Y or the Δ plan. By varying their arrangement, a considerable range of voltage may be secured without any change in the transformers. For example, assume that the pressure between any two of the main wires of a three-phase system is 1000 volts as represented in Fig. 162. Using three ordi-

nary single-phase transformers, the primary of each is connected across two of the outside wires in Δ fashion; *AB* being one primary, *AC* another, and *BC* the third. If the ratio of transformation is 10 : 1, the voltage in each secondary coil will be 100 volts; and if these are also connected in Δ, then the voltage between any two secondary conductors, such as *a* and *c*, will be 100 volts. Keeping the primary circuits as before, but changing the arrangement of the secondary coils from Δ to Y, the voltage between the secondary lines becomes 173 volts in Fig. 163; since each coil, such as *Hg*, generates 100 volts as before, but there are now two in series, so that the resultant pressure is $\sqrt{3} \times 100 = 173$ volts, as shown in Fig. 118. By changing the primary coils to Y connection, the pressure



Figs. 162, 163, 164, and 165. Connection of Transformers on Three-phase Circuits

for each coil *ML* in Fig. 164 is $1000 \div \sqrt{3} = 580$ volts, consequently the voltage between the secondary lines is only 58 volts. When both primary and secondary coils are Y connected (in Fig. 165) the ratio of transformation is 10 : 1, as in Fig. 162, and the pressure between secondary lines is 100 volts. In this way secondary voltages in the ratio of 100 : 173 : 58 may be obtained from the same supply conductors without changing the transformers except in their external connections.

The manner of arranging lamps upon a three-phase circuit is illustrated in Fig. 166, in which *AD*, *BD*, and *CD* represent respectively the coils of a three-phase generator or of three transformers with *Y* connection. Each group of lamps, such as *QR*, is connected between one main conductor *CG*, and the neutral point

H. If the three circuits feed equal numbers of lamps, as indicated at *R*, *S*, and *T*, it would not be necessary to have the neutral wire *DH*; but if they are not balanced, as at *V*, *Y*, and *N*, which is more likely in practice, the neutral wire is required in order to maintain equal voltages on the three branches. In that case the neutral carries the difference between the currents, so that lamps may be turned on or off without materially affecting the others, provided the conductors are of sufficient size to avoid any excessive drop.

The regulation of polyphase systems may be effected by placing in series with each feeder an ordinary single-phase regulator similar to those illustrated in Figs. 154–156. For two-phase circuits a regulator should be put in each phase, as, for example, in *EF* and in *GH* in Fig. 158. A three-phase system should have a regulator

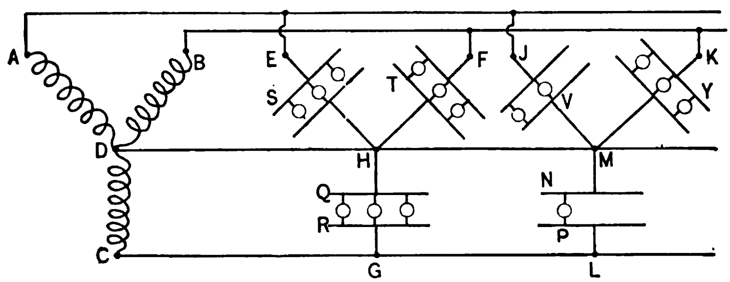


Fig. 166. Lamps on Three-phase Circuit.

in each of the three phases *A*, *B*, and *C* in Fig. 160. The use of independent regulators would enable the voltage to be adjusted separately in case the system is unbalanced, by reason of having differences in load on the three phases. With perfectly balanced loads, such as are produced by motors or by equal distribution of lamps, the three regulators should be adjusted alike, which may be accomplished by connecting them together mechanically.

A simpler plan for polyphase circuits is to employ the so-called *induction potential regulator* shown in Fig. 167, which controls the phases at the same time. It comprises a primary and a secondary winding, the former connected in shunt and the latter in series with the circuit. The *E.M.F.* generated in each phase of the secondary winding is constant; but by varying the relative positions of the two windings, this voltage may be added or opposed to the pressure of the circuit at any phase angle, so that the range of

regulation is from maximum "boosting" to maximum lowering. The principle is somewhat similar to that of the single-phase regulator in Fig. 155. The movable core may be rotated by means of a hand wheel, or when it is desired to operate it from a distance the apparatus is fitted, in addition to the usual hand wheel, with a small motor arranged to turn the core by means of gearing, as shown in Fig. 167. This motor may be of the direct current or induction type, and is controlled by a reversing switch mounted on the switchboard or at any convenient point.

Fig. 167. Induction Potential Regulator.

Induction Booster. — Another means of regulating the voltage in polyphase systems consists in connecting in series with the feeder to be regulated or compounded, the field magnet coils (*i.e.*, primary) of a small induction generator. For this purpose a machine similar to an ordinary two- or three-phase induction motor may be employed, but it must be driven by an engine or motor at a speed somewhat above that of synchronism. If no current is passing on the feeder, there will be no current induced in the armature of the machine, and no action whatever. But, as soon

as the current begins to flow in the feeder, it will induce current in the armature of the induction generator, which will react automatically on the field currents to add to their voltage. At any given speed above synchronism the boosting action depends in amount on the strength of the current in the feeder, while the action may be regulated by varying the speed at which the machine is driven. This evidently allows the main generator to be compounded or over-compounded without the use of sliding contacts, commutators or other objectionable apparatus, and also allows each feeder to be compounded separately, if desired, and all the feeders to be supplied from a single source of current.

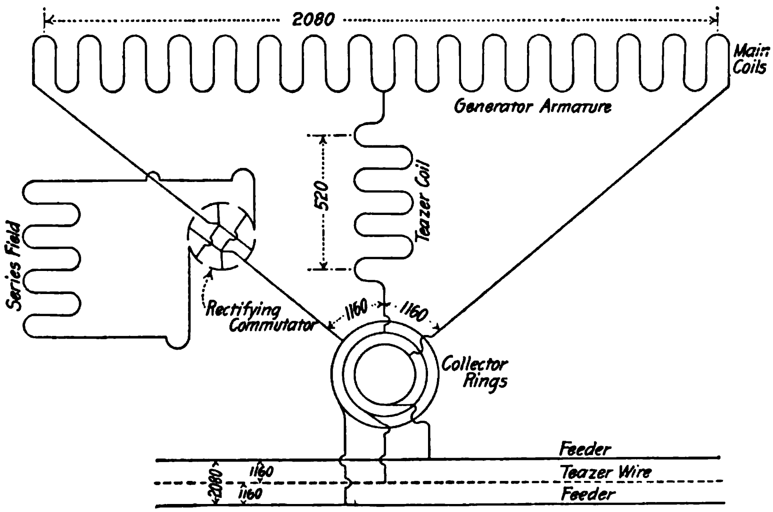


Fig. 168. Monocyclic Generator Connections.

The Monocyclic System. — The single-phase system is the simplest and best alternating current method when arc or incandescent lights are to be supplied, but no large number of motors, except perhaps, small fan motors, are to be operated. On the other hand, the polyphase systems are adapted to cases in which motors play an important part. The monocyclic system is a compromise between the two, being adopted for installations which supply lights for the most part, but are required also to operate motors. The lights are supplied from the main armature winding, which is practically the same as that of an ordinary single-phase generator. In addition to this main winding, the armature is provided with another set of coils, one terminal of which is connected to the middle

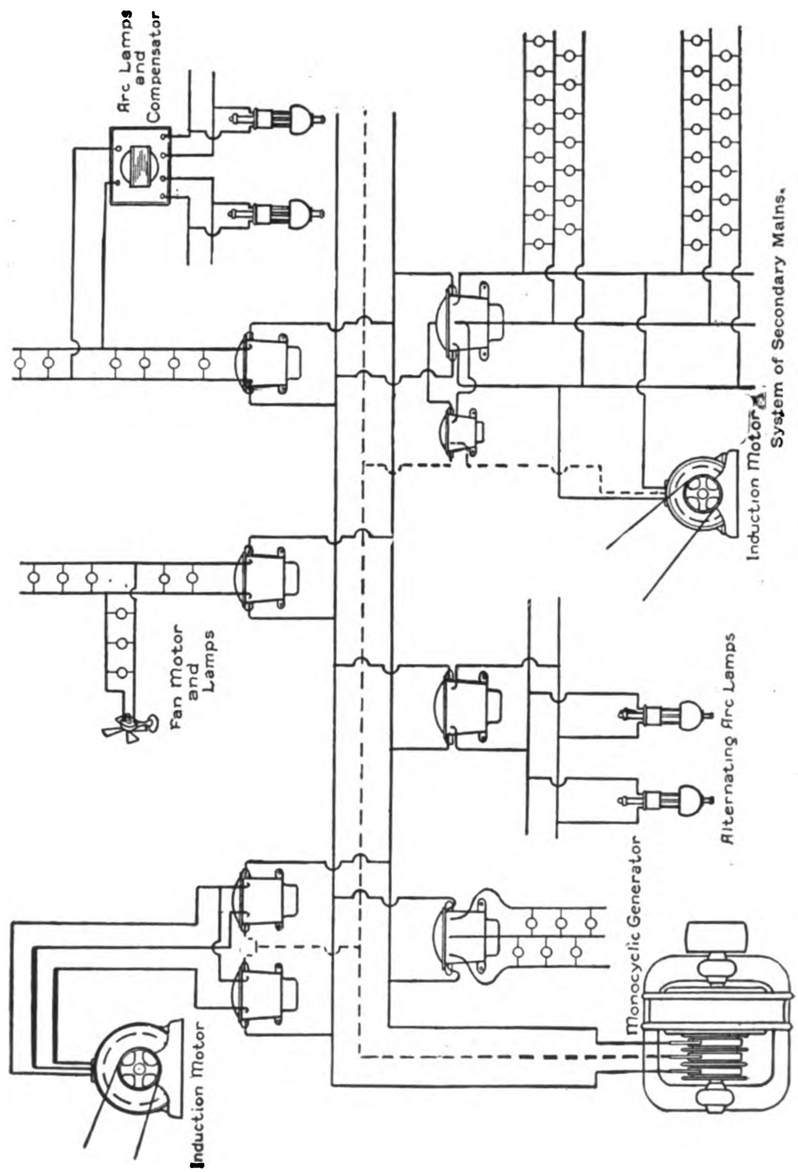


Fig. 169. Connections of the Monocyclic System.

point of the main winding, the other terminal being led to a third collector ring, as represented in Fig. 168. The auxiliary winding, called the "teazer coil," is so placed with respect to the other that they produce *E.M.F.*'s, differing by 90° in phase, and they are designed to give 520 and 2080 volts respectively. From the principles explained on page 126, it is evident that the *E.M.F.*, between the outer terminal of the teazer coil and either main terminal, is equal to $\sqrt{(1040)^2 + 520^2} = 1160$ volts. The main current is passed through a rectifying commutator to feed the series field coils, and produce a compounding effect similar to that in the single-phase composite-wound generator shown in Fig. 153.

The manner of supplying arc and incandescent lamps as well as motors by means of the monocyclic system is illustrated diagrammatically in Fig. 169. It will be observed that all the lights and small single-phase fan motors are supplied through transformers, the primaries of which are connected to the two outer or main conductors only. In other words, they are fed with ordinary single-phase current. The large motors may be of either the induction or synchronous types and are supplied through two transformers, connected, as shown, to all three conductors, so that they receive, in addition to the main current, another current differing in phase from the former, which enables them to be started up as polyphase motors.

For lighting purposes the usual forms of single-phase transformers are employed. In connection with motors the transformers may be specially designed for the monocyclic circuit, or a pair of simple single-phase transformers may be arranged as indicated in Fig. 170. In the latter case the primary coils P and Q are connected to the three supply conductors A, B, and C as shown, C being the auxiliary wire. The secondary coils S and T are connected in a similar manner, except that one of them is reversed, and the motor is fed by the three wires G, E, and F.

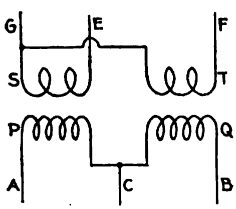


Fig. 170. Transformers on Monocyclic Circuit.

Polyphase Transmission and Direct Current Distribution. — An important use of the polyphase system in connection with electric lighting is for the transmission of energy at high potential from the generating plant to sub-stations, where it is converted into

low-tension direct current for local distribution. The object of this plan, which has been adopted by many of the largest electric light and railway companies, is to combine the advantages of both alternating and direct currents. The essential features of this system are indicated in Fig. 171. The generators *GG* are generally three-phase, since the conductors for this system require only three-quarters as much copper as for the two-phase system, the distance of transmission, voltage, percentage of drop and other conditions being the same. It is customary to employ a low frequency of 25 periods per second. This is rather too low for satisfactory arc or incandescent lighting; but the energy is con-

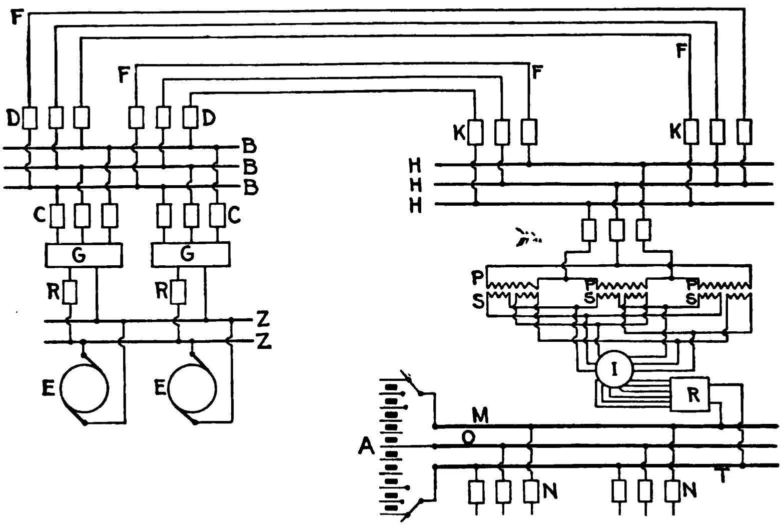


Fig. 171. Three-phase Transmission and Direct Current Distribution.

verted or rectified into direct current or the frequency may be raised by means of a "frequency change" before it is used for feeding lamps, so that this objection is avoided. On the other hand, the low frequency is better for transmission, because the effects of inductance and capacity are less, and, moreover, it facilitates the operation of the generators in parallel, which is the usual practice in such installations. In the United States a standard voltage of 6600 has been adopted, being considered to be as high a pressure as it is practicable to handle in machines, underground conductors, switches, fuses, circuit breakers, etc. This pressure is produced directly by the generators without step-up transformers, thus

saving the cost of, space occupied by, and losses in, the latter. Motors are also operated directly at this voltage in order to drive arc-lighting dynamos or other apparatus.

The generators *GG* are connected in parallel to the bus bars, *B*, *B*, *B*, through switches and oil circuit breakers (Fig. 172) or fuses *CC*. Means are also provided for bringing each machine into synchronism with those already running, before it is connected to the main bus bars, the usual indicating lamp or other device being employed for the purpose. The field magnets of all the generators are supplied in parallel from a set of direct current exciters, *EE*, in the ordinary manner. It is well to have a storage battery in parallel with the exciters in order to increase the reliability of the field excitation. The strengths of the fields and therefore *E.M.F.*'s of the generators are independently regulated by means of a rheostat, *R*, placed in each field circuit, which may be operated electrically.

From the main bus bars, feeders *FF* lead out through oil circuit breakers or fuses, *D*, and run to the sub-station or stations from which the energy is to be distributed. The drop on the feeders is either 5 or 10 per cent, giving 6300 or 6000 volts at the sub-station. These feeders are usually underground cables of the form described in the chapter on Underground Conductors. After the feeders enter the sub-station, they again pass through fuses or oil circuit breakers, *KK*, and then to the high tension bus bars, *HHH*, from which the primary circuits of the static transformers, *S*, are supplied through oil circuit breakers, *LL*. In these transformers the energy is stepped down from 6300 or 6000 to about 165 volts, and is then fed into rotary converters, *R*, which change it into direct current at about 270 volts.

The ratio of conversion from single- or two-phase to direct current is $1 : \sqrt{2} = 1 : 1.41$, since the latter corresponds to the maximum value of the former (p. 114). The three-phase *E.M.F.* is $\sqrt{3} \div 2$ times that of a single-phase *E.M.F.* obtained from the same rotary converter (p. 145). Hence the ratio of conversion from three-phase to direct current is $\sqrt{3} \div 2 : \sqrt{2} = .613 : 1 = 1 : 1.63$ with a sine wave of *E.M.F.*, and is not capable of much change, as stated on page 97. On account of the latter fact, the regulation of the direct current voltage is effected by means of induction regulators *I* of the form shown in Fig. 167 inserted in

the secondary circuits of the stepdown transformers *S*. These regulators are capable of raising or lowering by 30 volts, or about 10 per cent, the pressure produced by the rotary converters, which is 270 volts, hence the range of regulation is from 240 to 300 volts. Each rotary, *R*, of 1000 k.w. capacity is provided with its own regulator rated at about 130 k.w. The static transformers, *PS*, of 350 k.w. capacity each, are connected in groups of three with no cross connections between the groups on the secondary side; *i.e.*, there are no low-tension alternating current bus bars. Each group of three transformers feeds one rotary converter, to which the secondaries of the group are directly wired, there being no means of switching any rotary from one to another group of transformers. This arrangement is adopted to avoid the use of switches in the low-tension, heavy current alternating circuits, as well as to avoid the transference of stray direct currents from one rotary converter to another through the alternating current connections, which transference is likely to take place when two or more rotaries are electrically connected to the same low-tension alternating current bus bars.

In most cases the rotary converters are operated as *six-phase* machines. The purpose of this arrangement is to reduce the copper losses in the rotary armatures, and consequently raise the capacity of the rotaries with the same temperature rise. As rotary converters have no field distortion their capacity is determined solely by their heating limit and their commutating ability, so that any means of reducing the heating correspondingly increases the number of kilowatts which a given machine will convert, provided there is sufficient field strength to reverse the currents in the armature coils as their commutator segments pass under the brushes. It has been shown * that a machine which will deliver 100 kilowatts without overheating when driven mechanically as a generator, will deliver 131 kilowatts with the same temperature rise when run as a three-phase rotary converter, and will deliver 194 kilowatts when run as a six-phase rotary converter, other conditions remaining the same. This is allowing for the internal losses of the converter, and assuming that the impressed *E.M.F.* is in phase with the counter *E.M.F.* of the machine. If wattless currents are not carefully balanced out, or

* Steinmetz, The *Electrical World*, Dec. 17, 1898.

are used for purposes of regulation, the output of the machine with either number of phases falls off somewhat, but the six phases still show about the same advantage over the three phases. Assuming a wattless component amounting to 30 per cent of the total alternating current input of the machine, the same 100-k.w. generator would deliver 122 kilowatts as a three-phase rotary and 167 as a six-phase rotary. In addition to the reduction of the heating, the six-phase arrangement distributes the heating much more uniformly around the armature of the rotary than do three phases, with which the heating is rather badly concentrated in a few coils.

While the term "six-phase" conveys an idea of considerable complexity, it requires but very little modification of the usual three-phase arrangement. The generators and high-tension transmission lines are three-phase, the six phases being derived from the step-down transformers, which are of the usual single-phase type, and three in number, but have each two electrically independent secondaries. These six secondaries of the step-down transformers are connected in two separate Δ arrangements, one secondary of each transformer being reversed with respect to the other, thus producing currents differing 180° in phase. The connections of the three transformers are shown in Fig. 171, the primaries *P* being fed from the high-tension three-phase circuit arranged in Δ, the potential being either 6300 or 6000 volts, depending upon whether a drop of 5 or 10 per cent occurs on the feeders. Special taps are led from the primary coil to enable either voltage to be used. Each transformer has two secondaries which are connected in double Δ fashion, as represented, to give six-phase currents at about 165 volts which are carried through the induction regulator *I*. From the latter the six-phase energy passes to the rotary converter, *R* in which it is changed to direct current energy at about 270 volts. This energy is supplied to the outer bus bars *M* and *T*, from which it is distributed through feeders *N* to the ordinary three-wire network of conductors similar to that described on page 103. The drop on the feeders, mains and house-wiring reduces the potential to about 230 volts, so that the lamps receive about 115 volts on each side of the system.

Storage batteries are commonly employed in connection with these systems, being placed in the sub-stations, and charged from

the direct current side of the rotary connectors as represented at *A* in Fig. 171. The batteries serve to subdivide the potential for the three-wire system, and enable a more uniform load to be maintained on the generating plant, feeders, transformers, converters, etc., or allow them to be shut down temporarily. It affords also a means of starting up the rotary cônverters from their direct current sides.

The connections of a somewhat different distributing plant are shown in Fig. 173, which represents the arrangement at the North Avenue Sub-station of the Chicago Edison Company. In this case two three-phase rotary converters of 100 k.w. each are used, and the primary pressure is 4500 volts ; otherwise the installation is similar to that described in connection with Fig. 171.

Substantially the same system of three-phase transmission and direct current distribution is employed for electric railways, the only important differences being the facts that the direct current is produced 550 or 600 volts and the distribution is by two-wire instead of by three-wire circuits.

In spite of the step-down transformation and the con-

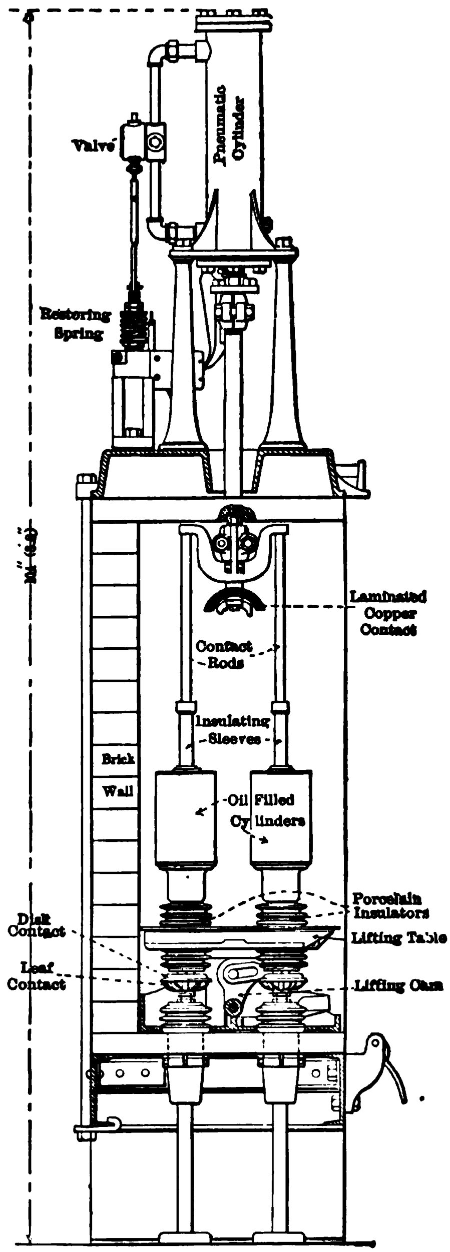


Fig. 172. Oil Circuit Breakers.

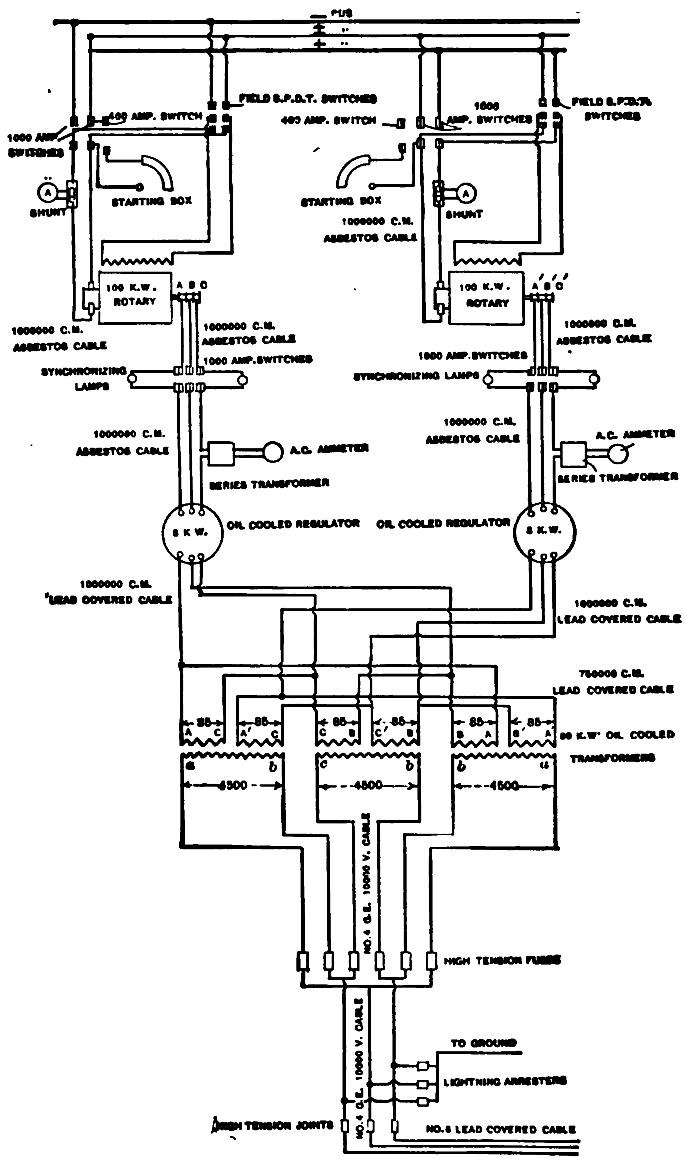


Fig. 173. Connections at Sub-station.

version from direct to alternating current, the efficiency of these systems is fairly high. The following figures have actually been obtained in practice.* The step-down transformers had an efficiency

* *Street Railway Journal*, October, 1899, p. 710.

of 98.2 per cent at full load of 350 k.w. each, and the rotary converters of 990 k.w. each gave 96 per cent efficiency at full load, making a combined efficiency of 94.2 per cent. In comparing this with a system using alternating current throughout, it should be remembered that the latter would require two sets of transformers to bring down the pressure from 6600 volts to that used in the lamps. In other words, a set of static transformers would be substituted for the rotary converters, so that the combined efficiency would be $98.2 \times 98.2 = 96.4$ instead of 94.2 per cent. On the other hand, it would not be possible to use direct current arc lamps or motors, storage batteries, or any electrolytic apparatus in connection with a purely alternating current system. Furthermore, losses and the difficulties of regulation, etc., caused by inductance, capacity, and low-power factor would occur with alternating current in the distributing conductors and house-wiring. In most practical cases these would more than offset the additional loss of 2.2 per cent in the rotary converters.

A form of oil circuit-breaker used in the very high-tension (6600 volts) circuits of this system is illustrated in Fig. 172. It consists of a magnet operating the valve of a pneumatic cylinder the piston of which raises or lowers a metal cross-head carrying three wooden rods that extend down into three cells, each containing the switching apparatus for one phase of the circuit. A section through one of these cells is shown in Fig. 172, the others being the same, and separated from each other by 4-inch brick partitions to act as barriers and prevent arcing between the switches. The actual circuit-breaking parts are connected to the movable rods and are submerged in oil. This type of circuit-breaker is rated at 10,000 volts and 800 amperes per phase.

In connection with the above-described system of three-phase transmission and direct current distribution, it is common practice to employ double current generators, rectifiers, and frequency changers, which will now be explained under their respective headings.

Double Current Generators. — Since a rotary converter is provided with a direct current commutator and with alternating current collecting rings connected to its armature winding (page 97), it may be employed as a generator if driven by an engine or other source of power, and polyphase or direct currents or

both may be obtained from it. In some plants these machines are used as converters at one time and as generators at other times. They may be run as polyphase generators to supply energy at a distance through step-up transformers, and can also be utilized to charge storage batteries with direct current, these two functions being performed at different hours of the day or at the same time, if desired. When so used they are termed double current generators. The use of these machines in the stations of the Chicago Edison Company is described in *The Electrical World and Engineer*, May 19, 1900, which also contains complete illustrations and description of the three-phase transmission and direct current distribution system employed on a very large scale by that company.

Rectifiers. — This name is given to those forms of apparatus in which single or polyphase alternating currents are changed into direct currents by means of *commutators;* these machines being without field magnets or armatures. This distinguishes them from rotary converters which are complete dynamo machines. Rectifiers are much simpler, cheaper, and more efficient than converters; nevertheless, they have not been very generally introduced, chiefly on account of practical difficulties in keeping them in adjustment and avoiding sparking.

In principle a rectifier is a reversing commutator *C* in Fig. 174, similar to that of an open-coil arc dynamo (Vol. I. p. 332). In

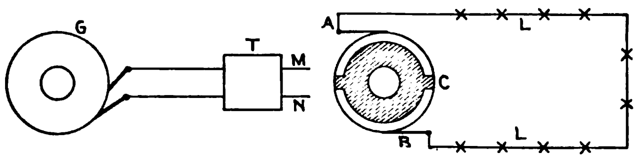


Fig. 174. Rectifier of Alternating Currents.

this case a two-part commutator is represented, one segment being continuously connected to one wire *M* and the other segment to the other wire *N* of the supply circuit. These connections are not shown, but are made through a pair of brushes and rings connected respectively to the two commutator segments. The wires *M N* lead from a single-phase generator *G* through a constant current transformer *T*, and it is evident that the connections

of the brushes $A\,B$ will be reversed at every half revolution of the commutator. If a circuit feeding arc lamps L in series be connected to brushes $A\,B$, it is evident that the current will flow through the lamps always in the same direction, provided the connections are reversed exactly when the alternating current reverses. In Fig. 175 the alternating current A, B, C, D, F, etc., is converted into the pulsating direct current A, B, C, E, F, etc., if the reversals occur at the points C, F, H, etc. It should be noted also that the current is zero at the instant of reversal, hence sparking is avoided. In order that the action shall take place correctly the commutator C must revolve synchronously and in proper phase with the alternating current. For a two-part commutator the number of revolutions per second must equal the frequency, and the brushes $A\,B$ must be set very carefully so that they pass from one commutator segment to another at the instant when the current is zero.

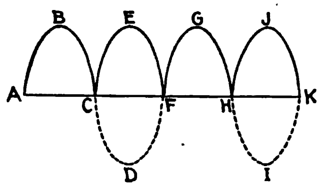


Fig. 175. Rectified Single-phase Current.

The constant current transformer T may be one of the forms already shown in Figs. 135, 136, and 137; and it will feed the lamps practically the same as if they were connected to it directly, except that the current through them will be unidirectional instead of alternating, thus allowing ordinary types of direct current arc lamps to be used. The fact that the current is pulsatory is not objectionable for arc lighting, since the standard Brush and Thomson-Houston arc dynamos produce currents of this character. Incandescent lamps may also be operated equally well with this current. A low frequency of 25 is too low for very satisfactory running of either kind of lamp, but at 40 or more periods per second both work well. The pulsating current is also applicable to the charging of storage batteries and to other electrochemical purposes; but for the operation of the ordinary direct current motors it would be likely to cause sparking unless the pulsations were "smoothed out" by inductance, storage batteries, or other suitable means.

Rectifiers have been more generally employed in England than in America, the Ferranti type being used in a number of stations. This consists essentially of a synchronous alternating current

motor driving the rectifying commutator. A constant current transformer with movable coils somewhat similar to that shown in Fig. 135 is employed in connection with this rectifier, which is usually applied to arc lighting.

An interesting example of rectifier is that installed by Mr. W. S. Barstow in Brooklyn. The 6600 volt three-phase current from the main generating station is supplied to the primary of a constant current transformer of the type illustrated in Fig. **135**, the secondary circuit at 6600 volts is led through the rectifier, which consists simply of a three-part commutator driven by a synchronous motor, the three-phase conductors being connected respectively to the three segments of the commutator. Two brushes set diametrically opposite each other are applied to the commutator, and are connected to a series circuit of arc lamps. The standard form of Thomson-Houston commutator is employed with the usual blower attachment to suppress sparking. Since the Thomson-Houston armature has practically a three-phase winding of the Y form, the current supplied to its commutator segments is practically the same as in a three-phase rectifier. In the latter case the commutator is placed at a distance from the armature winding, and is driven by a synchronous motor. Owing to changes in the phase of a motor when variations in load, etc., occur on the circuit, the position of the brushes may not agree exactly with the points of zero current, so that sparking will occur. Since the maximum potential exists between adjacent commutator segments separated only by a small air-gap, there is a strong tendency to flashing or "ring-fire" around the commutator, thus short-circuiting a pressure of several thousand volts. This constitutes the chief difficulty in the operation of rectifiers.

The direct current obtained by rectifying a two- or three-phase current does not pulsate so much as the rectified single-phase current in Fig. 175, for the reason that in the former case two or three waves are superimposed. If, for example, we reverse all the waves below the zero line in Figs. 110 and 114, the resulting direct current would be represented by a curve obtained by summing up the ordinates at every point, the fluctuations being much less than in Fig. 175.

Frequency Changers. — As their name implies, these machines are used for changing the frequency of an alternating current.

Ordinarily the object is to increase a low frequency of say 25 periods per second, which is hardly high enough for arc or incandescent lighting, to 60 periods for example, which is more satisfactory for the purpose and is also suited to the usual types of motors and transformers. The type of frequency changer made by the General Electric Company is essentially a polyphase transformer with a movable secondary. The latter consists of a secondary or armature suitably wound for any desired voltage and phase, which is mechanically revolved and acted upon by the rotating field of a polyphase primary. If the secondary is revolved in a direction opposite to that of the rotary field, obviously the frequency of the current in the secondary will be higher than the frequency of the current supplied to the primary, and *vice versa*. When the secondary rotates against the rotary field, it acts as a generator and requires power to drive it, and when it turns with the field the machine acts as an induction motor. Thus we see that there is a combined generator and transformer action when the frequency is raised.

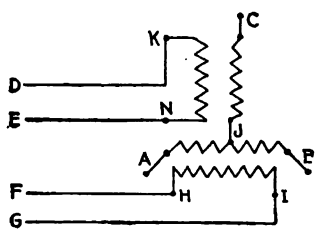
The secondary may be rotated by any suitable mechanical means, the synchronous polyphase motor being ordinarily used for this purpose. By over-exciting the field of the latter, the leading current thus produced (p. 134) may be made to balance the lag caused by the primary of the frequency changer, thereby raising the power factor on the supply circuit. The output of a frequency changer when the frequency is increased is equal to the sum of the mechanical power applied to it and of the electrical imput in the primary, less the losses. The frequency of the secondary current is equal to the number of poles of the primary, multiplied by the sum of the revolutions per second of the shaft and of the field (when they run in opposite directions). If the primary has a three-phase winding and the secondary is provided with a two-phase winding, the current is changed from three- to two-phase at the same time that the frequency is raised. It is evident also that the opposite change may be effected by transposing the windings.

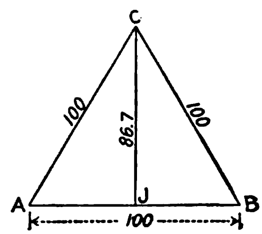
Tests of a 200 k.w. General Electric frequency changer of this type gave the following results :

Primary	wound for	6000 volts,	3 phase	and	25	cycles.
Secondary	"	" 2400 "	2 "	"	62½	"

The above machine was directly connected to a 4-pole, 3-phase, 6000-volt, 25-cycle (hence 750 *r.p.m*) synchronous motor with a stationary armature. The efficiency was 73½ per cent at 80 k.w. output, 81½ at 120 k.w., 87½ per cent at 160 k.w., and 91 per cent at 200 k.w. or full load. The power factor was practically 100 per cent at all these loads, showing the balancing of the lagging and leading currents as already pointed out. The wave forms of *E.M.F.* and current approximated closely to the simple sine curve. The efficiencies stated above signify the true watt output divided by the true watt imput, the latter including the true watts consumed by the motor.

Transforming from Two- to Three-Phase. — It has just been explained how the frequency changes may be employed to transform currents from two- to three-phase, or *vice versa*. This requires, however, two rather expensive machines demanding attention, so that when no change in frequency is desired, it is more economical to transform from two- to three-phase, or the converse, by means of simple static transformers. A method of this kind, devised by Mr. C. F. Scott,* is illustrated in Figs. 176–178. It





Figs. 176 and 177. Transforming from Two- to Three-phase.

involves the use of two transformers, one wound for a ratio of transformation of say 1000 : 100, and the other for a ratio of 1000 : 86.7. In Fig. 176, *HI* represents the primary and *AB* the secondary of the first transformer, *KN* and *CJ* being respectively the primary and secondary of the second transformer. The two primaries are fed from the two-phase circuit *DE* and *FG*, and one terminal of the secondary *CJ* is connected to the middle point of the secondary *AB*. The three-phrase circuit is connected to the points *AB* and *C*. In the diagram of potentials (Fig. 177) it is evident that *AC* and *CB* will each be equal to *AB*, so that *ABC*

* *Electric World*, March 17 and 24, 1894.

will be an equilateral triangle when $CJ : AB :: \sqrt{3} : 2 :: 86.7 : 100$, hence the three secondary *E.M.F*'s. represented by *AB*, *BC* and *CA*, are equal in value and differ by 120° in phase. This is the proper condition for supplying a three-phase circuit connected to the points *A*, *B* and *C*. In practice, especially in small transformers, it is a sufficiently close approximation if the *E.M.F.* of the secondary *CJ* is 90 instead of 86.7 per cent of *AB*.

This method is often employed when two-phase energy is produced by the generators (see Fig. 178) and it is desired to transmit some or all of it to a considerable distance. By transformation from two- to three-phase, a saving of twenty-five per cent in copper is secured in the transmitting conductors *A*, *B*, *C*. At the receiving station the energy may be distributed in three-phase form or may be transformed back again into two-phase current as indicated in Fig. 178. The large generators at Niagara are of the

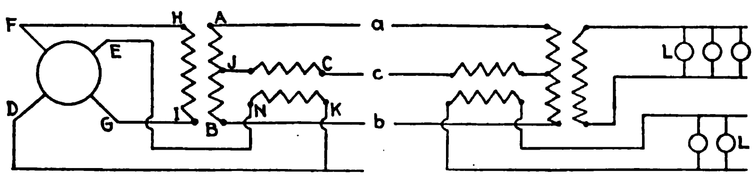


Fig. 178. Phase Transformation.

two-phase type, and some of the energy produced by them is transformed in the above-described manner, so that it may be transmitted in three-phase form.

Transforming from Single to Polyphase.—It is often very desirable to accomplish this result when it is required to operate motors from single-phase circuits, but the subject belongs to electric power more than to electric lighting. A method of this sort, invented by Mr. C. S. Bradley,* consists in causing, by means of a condenser, a lead of current in one branch of a circuit, and in combining this with lagging currents in another branch so as to produce a three-phase current in the secondary circuit.

Size and Location of Transformers.— Most systems of alternating current distribution employ transformers, and it is of great importance to exercise special care in deciding upon their sizes and locations. The constant core loss results in the course of a year

* Phasing Transformers *Trans. Amer. Inst. Elec. Eng.*, September, 1895.

in a waste of a large amount of energy, and every effort should be made to reduce this to a minimum. When transformers were first introduced, it was customary to use a large number of them in small sizes; but it was soon found that the core loss consumed too great a fraction of the total output of the station, often amounting to 25 and sometimes to 50 per cent. This was partly owing to the fact that transformers at that time were not as well designed and constructed as at present, but it was due also to the custom of using too many small sizes. This is made evident by inspecting the table on page 184, which shows that a 600 watt, 125-cycle transformer has a core loss of 20 watts, while one of 50,000 watt

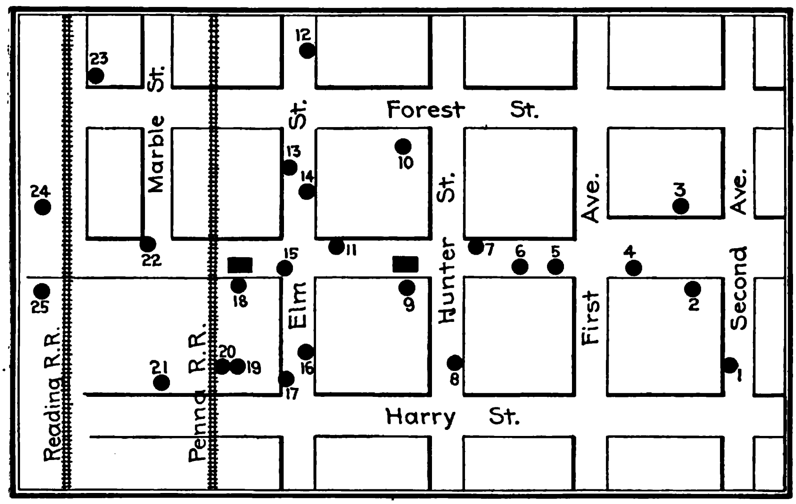


Fig. 179. Number and Arrangement of Transformer.

capacity, or 83.3 times as great, has a core loss of 354 watts, which is only 17.7 times as much. In the first case the loss is 3.3 per cent, and in the second it is but .7 per cent, or about one-fifth as large. If the comparison be made between the 1 k.w. and the 10 k.w. transformers, it is found that the former has a core loss of 2.5 per cent (25 watts) and the latter of 1.08 per cent; these being the limits of sizes ordinarily used in electric lighting.

The actual case of a district in a small town is represented in Fig. 179. Originally there were installed 25 small transformers (indicated by dots and numbers) having a combined capacity of 340 lamps of 16 c.p. and a core loss of 1664 watts. These were after-

wards replaced by two larger transformers (indicated by black rectangles), which had only 238 watts core loss, or about one-seventh as much, the saving being 1426 watts. If the first plant operated for 24 hours per day the core loss would have aggregated 40 k.w. hours for each day in the year, and probably this was greater than the useful energy consumed in the lamps. This may be a rather extreme case; but there were many others equally bad, and at one time the average practice was little better. Besides the advantage of lower percentage of losses in large transformers, a gain is made in the fact that the total required capacity is less. If, for example, a small transformer is installed for each house, it is necessary that its size should be sufficient to supply the maximum number of lights that will ever be used in that house at one time. Ordinarily, in fact for fully 99 per cent of the year, the number of lamps burning will be much less than this maximum, hence the transformer and its core loss are far out of proportion to the average useful current. On the other hand, a larger transformer, supplying ten houses for example, need not have ten times the capacity, because it is practically impossible that all of the houses will burn the maximum number of lights at the same time. In short, one 7.5 k.w. transformer will safely take the place of ten transformers of 1 k.w. each; and the former would have a core loss of only 85 watts compared with $10 \times 25 = 250$ watts for the latter.

A further saving may be effected by having sub-stations in which the transformers are concentrated or "banked," and connected in parallel. During the hours when the load is light, only one transformer need be operated, the primary circuits of all the others being open; but when the load increases transformers are added as required, thus the core loss is kept in reasonable proportion to the useful energy.

CHAPTER XI.

CALCULATION OF ALTERNATING CURRENT CIRCUITS.

THE properties of electrical conductors were given in Chapter I., which included a general discussion of economy in their design. The principles there laid down apply to alternating as well as to direct current conductors, but additional factors enter in connection with the former. In the long-distance transmission of power, these questions are of prime consequence; but in electric lighting the distances are ordinarily shorter, so that the problem is not so difficult or important. Hence it will not be necessary to consider the matter in detail or at great length in this work.

Choice of Frequency. — One of the first points to be decided in designing an alternating current system is the best frequency to employ. Those generally used in the United States are 25, 40, 60, 125, and 133 cycles per second. It would be well if the Standardization Report of the American Institute of Electrical Engineers were followed and three standard frequencies of 30, 60, and 120 became generally adopted. These would cover almost all cases that arise, and being simple multiples of each other would facilitate the design and construction of apparatus in regard to number of poles, windings, etc. In other countries many different frequencies are employed, 100 cycles being a common value in England and on the Continent. Sixty cycles or less is considered to be "low frequency," and above that is called "high frequency," but anything between 60 and 120 is rarely used in America. A frequency of 133 cycles was originally adopted when the alternating current was introduced for electric lighting, and is still used in many plants, especially those installed by the Westinghouse Company. A standard of 125 cycles is adopted for electric lighting apparatus by the General Electric Company. These high frequencies possess the advantage that the size and cost of transformers are less when they are selected. At the present time a 10 k.w. trans-

former costs about 25 per cent more for 60 cycles and about 60 per cent more for 25 cycles than for the high frequency of 125 cycles.

In the early history of alternating current lighting, the generators were belt-driven and ran at about 1000 r.p.m. Consequently 133 cycles could be obtained with a 16-pole machine. At present large direct-connected alternators running at about 100 r.p.m. are generally installed, and would require 160 poles to give the same frequency. This would make a complicated and expensive construction, so that 60 cycles, requiring 72 poles, would be much more practical. Another objection to high frequency is the fact that inductance or capacity effects are greater. The drop in voltage due to the former and the charging current due to the latter are both directly proportional to the frequency, and the tangent of the angle of lag is also proportional to it. For example, the voltage drop on a No. 0 A.W.G. wire due to its resistance and reactance (p. 116) is only one-half as much at 25 as it is at 125 cycles. Tables showing this difference will be given later in the present chapter. Since the drop is greater it follows that the regulation is poorer on high frequency circuits. The greater wattless currents cause greater heating in generators, lines, transformers, etc. Still another disadvantage of high frequency is the fact that it renders more difficult the parallel operation of generators and rotary converters, as well as the running of motors.

The disadvantages of low frequency, besides the higher cost of transformers already noted, are the difficulties involved in operating arc and incandescent lamps. It is not yet practicable to run the former below 40 cycles and the latter below 25 cycles per second, and even at those values the results are not very satisfactory. Low-voltage or large candle-power incandescent lamps flicker less than the standard 110 volt 16 c.p. lamps, but the practice is determined by the latter. The 220 volt lamp would be still more sensitive to the waves of current, on account of its thinner filament.

In conclusion, it may be said that for lighting alone at moderate distances a frequency of 125 or 133 may be adopted; but even in such cases it would probably be wiser to choose 60 cycles, in order to permit the operation of motors and the extension of the system to greater distances. For supplying power as well as light 60 cycles are very satisfactory where the circuits are not too long.

To transmit energy to great distances, a low frequency, such as 25 or 30 cycles, is suitable. The same is true of long underground or submarine cables where the capacity effects would be great. A low frequency of 25 is generally selected also for the simple transmission of energy between generating and distributing stations, where the energy is converted into direct current before it is used, so that the frequency makes no difference so far as the lights are concerned. This question, which is almost always a serious one, is often complicated by the fact that a certain frequency has already been adopted in the original plant, so that there is a great temptation to adhere to it in making additions. In many cases it may be necessary to do so; but frequently it would be wiser and cheaper in the end if the old-fashioned apparatus were sold, even at a great sacrifice, and a new plant designed and installed in accordance with the best practice.

Relative Weights of Copper for Various Systems. — This question is exceedingly important, but belongs more to long-distance power transmission than to electric lighting. Nevertheless, the problem often enters directly or indirectly in electric light engineering, and it will be well to consider briefly the principles involved, and the methods of calculation that are employed.

A comparison between the weights of copper required for the different direct-current systems was given on page 87. In attempting to apply similar reasoning to the alternating current, the difficulty arises that the voltage ordinarily *measured* is not the *maximum* value; and since the insulation is subjected to the strain of the latter, the relative figures obtained depend upon which basis of comparison is adopted. For long-distance transmission the highest voltage that is practicable under the circumstances would ordinarily be chosen, but for local distribution the effective pressure would determine the question.

The most important systems of transmission and distribution are represented in Fig. 180, and the relative weights of copper required are given in terms of the common two-wire circuit taken as 100. For equal *effective* values of *E.M.F.* the direct and alternating currents demand the same weight of copper; but if equal *maximum* values are considered, the latter requires twice as much copper, distances, power in watts, percentage of drop, etc., being equivalent. This is easily understood when we remember that the

maximum value of an alternating *E.M.F.* is $\sqrt{2} = 1.41$ times its effective rating, consequently an alternating *E.M.F.* of 100 volts would have the same maximum as a direct *E.M.F.* of 141 volts.

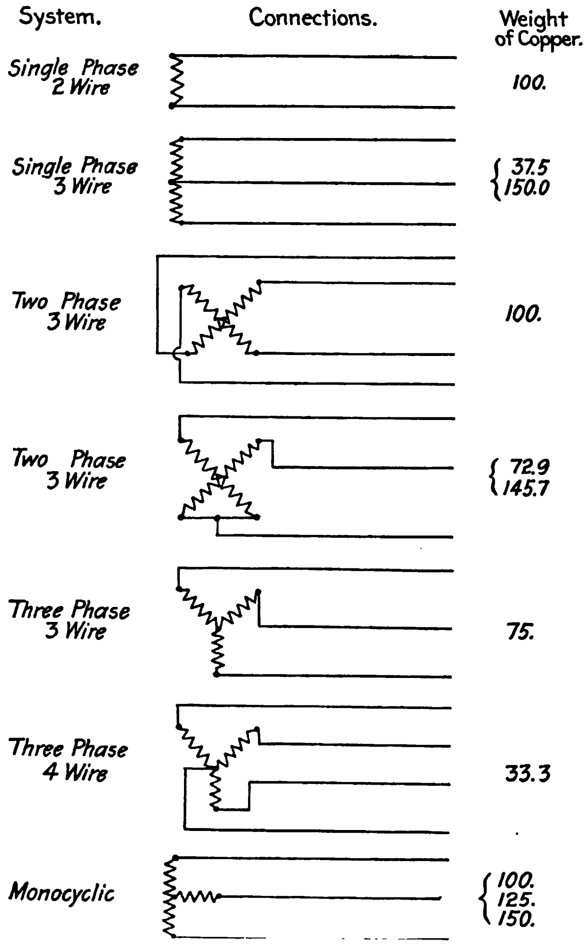


Fig. 180. Relative Weights of Copper.

For the same number of watts the amperes of the direct current are $\frac{100}{141}$ as great, so that the drop in volts is in the same proportion with equal resistances. But the *percentage* of drop is only $\frac{100}{141} \times \frac{100}{141} = \frac{1}{2}$ as large for the current, or one-half as much copper

would be required for the same percentage of drop. This is simply a particular case under the general law that *weight of copper is inversely proportional to the squares of the voltages, other things being equal.*

The single-phase, three-wire (Fig. 150) requires $37\frac{1}{2}$ per cent as much copper as the two-wire system, and by making the neutral one-half the cross-section of either of the outside conductors the copper is reduced to $31\frac{1}{4}$ per cent. These percentages are in the same proportion as for direct-current systems, the figures for which were explained on pages 72 and 87. The above ratios assume that the lamp voltages are equal in all cases; but it is evident that this will give twice the *total* voltage for the three-wire circuit, since it practically involves the placing of two lamps in series. For the same *total* voltage, the three-wire would require 50 per cent more copper than the two-wire system, since the former would have three conductors instead of two, and everything else would be the same.

Two-phase four-wire require the same amount of copper as the ordinary single-phase two-wire circuits, the former being equivalent to two single-phase systems. With the two-phase three-wire system (p. 142) the case is not so simple, but may be determined as follows: Assume the voltage V between either outside wire and the common return wire to be the same as in a single-phase circuit. The total power transmitted is VI for the latter, where I is the current, and to transmit the same power by the two-phase system the power must be $2\ Vi$, in which i is the current in either outside wire, and is equal to $I \div 2$. The current in the common conductor is $i\ \sqrt{2}$, consequently to have the same current density, which is the condition of maximum efficiency, its cross-section must be $\sqrt{2}$ times that of either of the others, and its resistance is $r \div \sqrt{2}$ in which r is the ohmic resistance of one of the outer wires. The loss of power for each of the latter is i^2r, and for the middle wire it is $2\ i^2r \div \sqrt{2} = i^2r\ \sqrt{2}$, hence the total loss in the three wires is $2\,i^2r + i^2r\sqrt{2} = i^2r\,(2 + \sqrt{2}) = I^2r\,(2 + \sqrt{2}) \div 4$, since $i = I \div 2$. The loss in the equivalent single-phase circuit is $2I^2R$, in which R is the resistance of one of the conductors, and this must be the same as the loss for the two-phase system; hence

$$2\ I^2R = \frac{I^2r\ (2 + \sqrt{2})}{4} \text{ or } r = \frac{8R}{2 + \sqrt{2}}.$$

Therefore each outer wire must be $(2 + \sqrt{2}) \div 8$ times, and the middle wire $\sqrt{2}\,(2 + \sqrt{2}) \div 8$ times as large as each single-phase conductor. It follows that the *weight of copper in the two-phase, three-wire conductors is* $\dfrac{2\,(2 + \sqrt{2})}{8} + \dfrac{(2 + \sqrt{2})\,\sqrt{2}}{8} = 1.457$ *compared with* 2 *for the single-phase, two-wire system, or in other words is* 72.9 *per cent as great at the same minimum voltage.* If this comparison is made on the basis of *maximum* voltage, it is necessary to make the potential difference between the outer conductors equal to that in the single-phase, two-wire circuit, hence the voltage between either outside wire and the common return is $V \div \sqrt{2}$, and the current in each branch $i_1 = I \div \sqrt{2}$, so that the power in both branches is $2\,(V \div \sqrt{2})(I \div \sqrt{2}) = VI$, which is the same as that in the single-phase system. The current in the common return is $i_1\,\sqrt{2} = I$, and its resistance should be $r_1 \div \sqrt{2}$ if r_1 is the resistance of each outer wire. The total loss is

$$2i_1^2r_1 + \frac{i_1^2 2r_1}{\sqrt{2}} = i_1^2 r\,(2 + \sqrt{2}) = I^2 r_1\,\frac{(2 + \sqrt{2})}{2}\,.$$

This must be equal to $2I^2R$, the loss in the single-phase, hence

$$I^2 r_1\,\frac{(2 + \sqrt{2})}{2} = 2I^2R, \text{ or } r_1 = \frac{4R}{2 + \sqrt{2}}\,.$$

That is, each outside wire requires $\dfrac{2 + \sqrt{2}}{4}$ times, and the middle wire $\dfrac{(2 + \sqrt{2})\,\sqrt{2}}{4}$ times as much copper as each of the single-phase conductors.

Hence the total system demands

$\dfrac{2\,(2 + \sqrt{2})}{4} + \dfrac{(2 + \sqrt{2})\,\sqrt{2}}{4} = 2.914$ compared with 2 for the single-phase, or 1.457 times as much copper; that is, *the two-phase three-wire system requires* 45.7 *per cent more copper than the two-phase at the same maximum voltage.*

Considering a three-phase, three-wire system (p. 145), having a voltage V between the lines measured as Δ potential, the current in each line, or Y current, is i_2, and the current from line to line, or Δ current, is $i_2 \div \sqrt{3}$. Hence the total power in all three branches is $3\,Vi_2 \div \sqrt{3} = Vi_2\sqrt{3}$, and if this is to equal VI, the power of the single-phase circuit, then $VI = Vi_2\sqrt{3}$, or $i_2 = I \div \sqrt{3}$.

If r_3 is the resistance of each three-phase conductor, then the loss per wire is $I^2r_3 \div 3$, and the total loss is I^2r_3, while in the single-phase system it is $2I^2R$. Hence, to get the same loss, $I^2r_3 = 2I^2R$, or $r = 2R$; that is, each three-phase wire has twice the resistance and half the copper of each single-phase conductor, or in other words, *the three-phase, three-wire system requires* 75 *per cent as much copper as the single-phase at the same maximum voltage.* In the three-phase, three-wire system, with the lamps connected between the neutral point and the three outer wires, — that is, in Y fashion (p. 144),— the voltage between the outer wires, or Δ potential, will be $V\sqrt{3}$, if V is the lamp or Y voltage. In other words, the potential between lines is raised from V to $V\sqrt{3}$; and since it has been shown previously that the weight of copper is inversely as the square of the voltage, the weight of copper for the three wires will be one-third as great as in the preceding case, and $\frac{1}{3} \div \frac{3}{4} = \frac{1}{4}$ as much as for the two-phase. The addition of a fourth or neutral conductor (Fig. 166) will increase this to $\frac{4}{3} \times \frac{1}{4} = \frac{1}{3}$, so that *the three-phase, four-wire requires* 33.3 *per cent as much copper as the single-phase, two-wire system at the same minimum voltage.*

The monocyclic system, when supplying lamps, is practically the same as a single-phase circuit (p. 208); and most of the energy for motors is carried by the two main conductors, except in starting, when the auxiliary wire furnishes a certain amount of current. If the extra wire is omitted on certain circuits, then the copper required is the same as for the single-phase, two-wire system. If the third wire is one-half as large as each of the other two, then the monocyclic calls for 125 per cent; and if the three conductors are all of the same size, then the copper demanded is 150 per cent of that used by the single-phase circuit. Hence *the monocyclic system requires as much copper as an equal voltage single-phase, two-wire system, plus the copper in the auxiliary conductor.*

This table is issued by the General Electric Company, and gives in convenient form the constants to be used in calculating overhead electric transmission lines, the various quantities having the following significance: —

r = Ohmic resistance.

L = Inductance in milhenrys per 1000 feet of conductor.

C = Capacity in microfarads per 1000 feet of conductor.

i_0 = Charging current at 100 cycles and 10,000 volts to neutral, that is, in a 20,000 volt single-phase, and a 17,300 volt three-phase line.

$i_0 = 2 \times \pi \times$ frequency $\times C \times E \times 10^{-6}$; where E is the *E.M.F.* between a line and neutral.

x = reactance $= 2 \times \pi \times$ frequency $\times L \times 10^{-3}$.

The *E.M.F.* consumed by resistance r, of the line, is $= Ir$, and in phase with the current I.

The *E.M.F.* consumed by the reactance x, of the line, is $= Ix$, and in quadrature with the current I.

The *E.M.F.* consumed in the line is neither Ir nor Ix, but depends upon the phase relation of current in the receiving circuit.

The loss of energy in the line is $= I^2r$, hence does not depend upon the reactance, but only upon the resistance.

Two wires in parallel have the same resistance and about half the reactance (if strung on separate insulators and intermixed) of a single wire of double cross-section. Thus replacing one No. 0000 wire by two No. 0 wires, the resistance, weight of copper, etc., will remain the same, but the reactance will be reduced practically to half, so where lower reactance is desired, the use of several conductors, strung on independent insulators and intermixed, is advisable.

The values given for L, C, i_0, and x are calculated for sine waves of current and *E.M.F.*

LINE CONSTANTS FOR ELECTRIC TRANSMISSION.

PER 1000 FEET OF EACH WIRE.

SIZE OF WIRE A.W.G.	WEIGHT.	DIAMETER.	AREA IN CIRCULAR MILS.	RESISTANCE AT 75° F.	INDUCTANCE IN MILHENRYS.	CAPACITY IN MICROFARADS.	CHARGING CURRENT.	REACTANCE AT 25, 60, 125 CYCLES, IN OHMS.		
No.	Lbs.	Mils.	C.M.	r	L	C	i_0	× 25	× 60	× 125
0000	639	460	211600	.049	.282	.00388	.0244	.0443	.1062	.221
000	507	410	167805	.062	.290	.00378	.0238	.0455	.1090	.227
00	402	365	133079	.078	.296	.00368	.0232	.0465	.1113	.232
0	319	325	105592	.098	.303	.00358	.0226	.0476	.1141	.238
1	253	289	83694	.124	.310	.00351	.0220	.0486	.1166	.243
2	201	258	66373	.156	.317	.00342	.0215	.0498	.1194	.249
3	159	229	52633	.197	.324	.00334	.0210	.0509	.1220	.254
4	126	204	41742	.249	.332	.00326	.0205	.0521	.1248	.261
5	100	182	33102	.314	.339	.00320	.0201	.0532	.1277	.266
6	79	162	26250	.395	.346	.00313	.0197	.0543	.1301	.271
7	63	144	20816	.499	.352	.00306	.0193	.0553	.1327	.276
8	50	128	16509	.629	.360	.00300	.0189	.0565	.1355	.283
9	40	114	13094	.792	.366	.00294	.0185	.0575	.1380	.288
10	31	102	10382	.999	.373	.00288	.0181	.0585	.1405	.293

The above figures apply to parallel wires that are 18 inches apart, but are not much modified by moderate changes in interaxial distance. For example, the inductance L is decreased about 10

per cent when the wires are 12 inches apart, and is increased about 10 per cent when they are put 30 inches apart. A similar change would be produced in the reactance $2\pi fL$. The capacity C and charging current i_0 are increased about 10 per cent, if the interaxial distance is reduced to 12 inches; and is decreased about 10 per cent when it is raised to 30 inches. For wires placed close together in cables, the inductance and reactance would be greatly reduced, and the capacity and charging current greatly augmented, so that their values in the table would not be even approximately true. In such cases, or whenever there may be any doubt, the general formulæ for inductance and capacity, given on pages 129 and 137 respectively, should be used. The table on page 130 shows the inductance of wires from No. .0000 to No. 12, and for interaxial distances from 3 to 96 inches.

The equations on page 138 give results for capacity that are twice as great as those found in the above table, the reason being that each conductor is considered separately with respect to *zero potential*, which would ordinarily exist at a point midway between two wires forming a circuit; whereas the equations (p. 138) give the capacity with respect to the *other wire*, which is one-half as much. The calculated charging current would be the same in both cases, because the total voltage would be used in one instance, and the potential with respect to zero is taken in the table. The latter plan is generally better. Other convenient tables issued by the General Electric Company are given below. They apply particularly to overhead circuits with wires 18 inches apart, and are sufficiently accurate for most practical purposes, when the distance between wires is approximately that amount. If the conductors are less than 18 inches apart, the loss in voltage is lower than that given by the formulæ, and if they are close together, as in cables or interior wiring, the loss will be only that due to resistance.

The following general formulæ may be used to determine the size of copper conductors, current per conductor, volts loss in lines, and weight of copper per circuit for various systems of electrical distribution.

$$\text{Area of conductor, Circular Mils} = \frac{D \times W \times K}{P \times E^2}. \qquad (77)$$

$$\text{Current in main conductors} = \frac{W \times T}{E}. \qquad (78)$$

$$\text{Volts loss in lines} = \frac{P \times E \times M}{100}. \tag{79}$$

$$\text{Lbs. copper} = \frac{D^2 \times W \times K \times A}{P \times E^2 \times 1{,}000{,}000}. \tag{80}$$

W = Total watts delivered.

D = Distance of transmission (one way) in feet.

P = Loss in line in per cent of power delivered, that is of W.

E = Voltage between main conductors at receiving or consumer's end of circuit.

For continuous current $K = 2160$, $T = 1$, $M = 1$, and $A = 6.04$.

CONSTANTS FOR ELECTRICAL CIRCUITS.

System.	Values of A.	Values of K. Per Cent Power Factor. 100	95	85	80	Values of T. Per Cent Power Factor. 100	95	85	80
Single-phase . .	6.04	2160	2400	3000	3380	1.00	1.05	1.17	1.25
Two-phase (4-wire)	12.08	1080	1200	1500	1690	.50	.53	.59	.62
Three-phase (3-wire)	9.06	1080	1200	1500	1690	.58	.61	.68	.72

VALUES OF M.

No. of Wire. A. W. Gauge.	25 Cycles. Per Cent Power Factor. 95	90	85	80	60 Cycles. Per Cent Power Factor. 95	90	85	80	125 Cycles. Per Cent Power Factor. 95	90	85	80	No. of Wire. A. W. Gauge.
0000	1.23	1.29	1.33	1.34	1.62	1.84	1.99	2.09	2.35	2.86	3.24	3.49	0000
000	1.18	1.22	1.24	1.24	1.49	1.66	1.77	1.95	2.08	2.48	2.77	2.94	000
00	1.14	1.16	1.16	1.16	1.34	1.52	1.60	1.66	1.86	2.18	2.40	2.57	00
0	1.10	1.11	1.10	1.09	1.31	1.40	1.46	1.49	1.71	1.96	2.13	2.25	0
1	1.07	1.07	1.05	1.03	1.24	1.30	1.34	1.36	1.56	1.75	1.88	1.97	1
2	1.05	1.04	1.02	1.00	1.18	1.23	1.25	1.26	1.45	1.60	1.70	1.77	2
3	1.03	1.02	1.00	1.00	1.14	1.17	1.18	1.17	1.35	1.46	1.53	1.57	3
4	1.02	1.00	1.00	1.00	1.11	1.12	1.11	1.10	1.27	1.35	1.40	1.43	4
5	1.00	1.00	1.00	1.00	1.08	1.08	1.06	1.04	1.21	1.27	1.30	1.31	5
6	1.00	1.00	1.00	1.00	1.05	1.04	1.02	1.00	1.16	1.20	1.21	1.21	6
7	1.00	1.00	1.00	1.00	1.03	1.02	1.00	1.00	1.12	1.14	1.14	1.13	7
8	1.00	1.00	1.34	1.00	1.02	1.00	1.00	1.00	1.09	1.10	1.09	1.07	8
9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.06	1.06	1.04	1.02	9
10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.04	1.03	1.00	1.00	10

The value of K for any particular power factor is obtained by dividing 2160, the value for continuous current, by the square of that power factor for single-phase, and by twice the square of that power factor for three-wire, three-phase, or four-wire, two-phase.

The value of M depends on the size of wire, frequency, and power factor. It is equal to 1 for continuous current, and for alternating current with 100 per cent power factor and sizes of wire given in the preceding table of wiring constants.

The value of T depends upon the system and power factor. It is equal to 1 for direct current and for single-phase current of 100 per cent power factor.

The value of A and the weights of wire in the table are based upon .00000302 lb. as the weight of one mil foot of copper.

It should be observed that P stands for the per cent loss of the *delivered power*, and not the per cent loss of the power at the generator; and that E is the potential at the end of the line, and not at the generator.

When the power factor cannot be more accurately determined, it may be assumed to be as follows for any alternating current system operating under average conditions: Lighting with no motors, 95 per cent; lighting and motors together, 85 per cent; motors alone, 80 per cent. The size of wire in (77) is for *each* of the main or outside conductors of a given system, for example, the three wires of a three-phase, the four wires of a two-phase, or the main two wires of a monocyclic system. The neutral wire in the three-wire system for direct (p. 72) or alternating currents (p. 192) may in the case of feeders be made one-half or one-third size, or omitted entirely (p. 76), depending upon how well the system may be balanced. For local or secondary circuits it should generally be the same size as each of the main wires. These statements also apply to the middle wire of the four-wire, three-phase arrangement (Fig. 166). The size of the auxiliary conductor in the monocyclic system should be in the same proportion to either main wire as the motor load in amperes is to the total load in amperes.

A simple method of calculating the drop and other data of alternating current circuits is represented in Fig. 181, being derived from the little book on *Alternating Current Wiring and Distribution*, by W. L. R. Emmet. Assume a case where 500 incandescent lamps, of 57.5 watts each, are to be fed from the sec-

ondaries of transformers of different sizes, being half loaded on the average. The primaries are supplied by two No. 2 wires from the generator two miles distant, the wires being 18 inches apart, and the frequency of 125 periods per second. The voltage of the lamps is 100, and the ratio of transformation is 10. In Fig. 181 the horizontal lines represent energy components, and the vertical lines inductive components of *E.M.F.* For the sake of uniformity the lamp voltage is multiplied by 10, the ratio of transformation making 1000 volts, which is represented by the horizontal line *AB*, since incandescent lamps are practically non-inductive. Assuming the secondary wiring to have an energy loss of 3 per cent, *BC* is laid off as 30 volts, and an inductance component *CD*, of the same amount. (Both of these are rather high values.) Take the resistance in the transformers at 1 per cent, and the inductance loss at

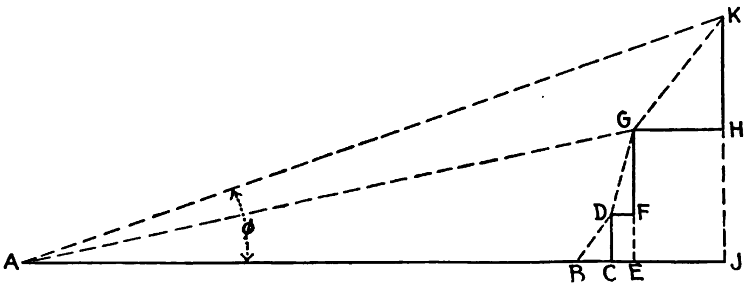


Fig. 181. Graphical Calculation of Alternating Current Circuit.

one-half load as 12.5 per cent of *AD*, or about 13 per cent. Hence we lay off $DF = 10$ volts to represent resistance, and $FG = 130$ volts to represent inductive loss in the transformers. If there were no losses in the transformers, the current received by them would be 28.75 amperes, but with 5 per cent iron loss at half-load this becomes 30.19 amperes. The resistance cf four miles of No. 2 wire from the table on page 8 is $.156 \times 5.28 \times 4 = 3.3$ ohms, and the reactance at 125 cycles is $.249 \times 5.28 \times 4 = 5.25$ ohms. To this we add 15 per cent for distortion of current waves, making 6.04 ohms. The resistance drop is $30.19 \times .33 = 99$ volts, and the reactance drop is $30.19 \times 6.04 = 1.82$ volts, which are laid off as *GH* and *HK*. Hence the line *AK* represents the *E.M.F.* required at the generator terminals, being 1188 volts. Extending *KH* to *J*, we have *AJ* the total energy component of 1139 volts, therefore the real power in the circuit is $11.39 \times 30.19 = 34{,}300$

watts, while the volt-amperes at the generator are 35,800, so that an alternator of 36 k.w. capacity will be required; but the power to drive it, assuming its efficiency at 90 per cent, will be 34.3 ÷ .90 = 38 k.w., or 51 h.p. The generator should be overcompounded about 19 per cent to be self-regulating.

Arithmetical Determination. — The same result that has been obtained graphically may be found arithmetically, as follows:

	Energy Component in Volts.	Inductance Component in Volts.	Current in Amperes.
Lamps brought to basis of 1000 volts . . .	1000		28.75
Secondary wiring with 3 per cent resistance and 3 per cent inductance loss	30	30	
	1030	30	
Transformer resistance loss of 1 per cent . . .	10		
" inductance loss of 12.5 per cent of volts at secondary terminals		130	
Primary current increased 5 per cent by core loss at half-load			1.44
Line current			30.19
Line resistance loss 3.3 × 30.19	99		
" inductance loss 6.04 × 30.19		182	
	1139	342	

Taking the square root of the sum of the squares of 1139 and 342, we find 1188 volts to be the *E.M.F.* pressure at the generator terminals, being the same as obtained by measurement in Fig. 181.

CHAPTER XII.

OVERHEAD CONDUCTORS.

THE term overhead conductors is applied to aerial electrical wires or cables carried on poles or upon brackets or other supports attached to buildings. The same general construction is used for telegraph and telephone, as well as for electric light and power lines; but the parts are usually heavier, and the insulation higher, in the case of the two latter, because of the larger size of the conductors and the more powerful character of the currents.

Materials for Overhead Conductors.—For electric light and power purposes copper is generally employed, and has now largely supplanted iron wire even for telegraph and telephone lines. The fact that hard-drawn copper has a tensile strength of 60,000 to 70,000 lbs. per square inch, compared with 25,000 to 35,000 for soft or annealed copper, makes it especially suitable for overhead construction. On the other hand, the specific resistance of hard copper is from 2 to 4 per cent greater, and it is much more brittle, so that it is not used for underground conductors or interior wiring where its greater tensile strength is not of much advantage. The fact that it is far less flexible makes it awkward to handle; consequently, hard copper is not convenient even for overhead conductors when they are of large size, or are covered with insulation. The resistances, weights, and other data of copper wires are given on pages 8 and 15, and in Chapter XI.

Aluminum has a specific resistance about .6 that of copper, both being of pure commercial quality, therefore the sectional area of equivalent conductors would be about 1.67 times and the diameter 1.3 times greater for aluminum. The specific gravity of aluminum is about 2.7, and of copper 8.89 (page 8), so that an equal volume of the latter weighs 3.3 times as much. A copper wire would be ($3.3 \div 1.67 = 2$) about twice as heavy as an aluminum wire of the same length and resistance. This is a great

advantage for overhead conductors, since it reduces the weight on poles, cross-arms, insulators, etc., by one-half.

The tensile strength of aluminum wires is about 20,000 to 30,000 lbs. per square inch; but the addition of a small percentage of copper increases this considerably, and alloyed with 2½ per cent of copper it becomes nearly 40,000 lbs. per square inch. On the other hand, the resistance is increased about 20 per cent, so that the advantage is doubtful. Furthermore, it has been found in practice that wires made of these alloys are likely to break, even when the tests of a sample show an ample tensile strength. This is due to the difficulty of making perfect alloys of aluminum, because the light metal does not readily form a thorough and homogeneous mixture with the copper, which has a density 3.3 times greater. The result is that flaws seem to exist at certain points on the wire, and a break may occur without excessive strain. In a case cited by Mr. P. N. Nunn * an average of *one break per span* occurred on a long transmission line composed of aluminum alloy.

The following data for commercially pure aluminum wire are taken from the paper itself, and agree closely with those already given:

Diameter of aluminum wire	293.9 mils.
Wt. per mile	419.4 lbs.
Resistance per mil foot	17.6 ohms at 25° C.
Resistance per mile at 25° C.	1.00773 ohms.
Conductivity compared with copper	59.9% by dimension.
Tensile strength of wire	1549 lbs.
No. of twists in six inches for fracture	17.9.
Tensile strength per square inch	32898.

Comparing this with copper, it is seen that this wire is approximately the same as copper in the following sizes: —

Size of aluminum wire	= No. 1 B. & S. copper.
Resistance of " "	= No. 3 " "
Tensile strength " "	= No. 5 " "
Weight of " "	= No. 6 " "

Therefore on the basis of the same conductivity the aluminum compares with copper as follows: —

* Discussion of a paper "On the Use of Aluminum Line Wire," by Perrine and Baum, *Trans. Amer. Inst. Elec. Eng.* May, 1900.

Diameter for the same conductivity	1.27	times copper.
Area " " " "	1.64	" "
Tensile strength " "	.629	" "
Weight " "	.501	" "

The number of twists necessary for fracture varies considerably, although the ductility test of wrapping six times around its own diameter, unwrapping and wrapping again, is well sustained. This irregularity in the twisting-test is generally a mark of impurity in wire; but we know so little as yet of the exact characteristics of aluminum in particular, and the twisting-test is in general so unreliable, that it is unsafe to base any exact statement on this one test, particularly as the wire after erection proved reliable. In carefully performing the test for tensile strength, no exact point could be assigned for the elastic limit, as the metal seemed to take a permanent set almost from the first; but at a stress of from 14,500 lbs. to 17,000 lbs. per square inch, there is a marked increase in the permanent set which indicates that the safe working-load lies somewhere in this region. In this the characteristics of aluminum do not differ materially from those of copper or other similar metals; and while this is a disadvantage, it is not a singularity.

The fact that the wire will permanently elongate if seriously strained makes it necessary to use the utmost care in the erection of lines, and also the known high coefficient of expansion with temperature changes taken in conjunction with this property renders care in line-stringing especially important and difficult. The greatest care must be taken against kinking or scarring the wire; wherever the wire is accidentally kinked or scarred, it must be cut and spliced.

One of the most serious problems in connection with the use of aluminum is in the choice of a proper joint. This metal is so highly electro-positive that it is unsafe to expose it to the elements in contact with any other material, as electrolytic corrosion is almost sure to follow such construction. Many of the failures which have been reported of this metal have been due to a neglect of this fact. Whenever this metal is soldered, or used in contact with any other metal, the joint should be thoroughly waterproofed to prevent such action. Without such protection the joints may be made by slipping the ends of the wire into an oval aluminum tube about nine inches long, which is then twisted about two and

a half turns, with a pair of clamps similar to those employed in twisting the McIntire connector. The joint produced is practically equal to the original wire in both tensile strength and electrical conductivity.

Tests made at the Columbia University showed the fusing points of pure aluminum wires suspended horizontally in the open air to be 180 amperes for No. 8, 135 amperes for No. 10, and 60 amperes for No. 14 A. W. G. For aluminum alloyed with 1 per cent copper, the fusing-points were 163 amperes for No. 8, and 54 amperes for No. 14 wire.

The use of aluminum as an electrical conductor may be summed up as follows: It is especially advantageous for bare overhead lines, because it weighs only one-half as much as copper for the same resistance and length, thus reducing to one-half the weight to be carried by insulators, cross-arms, and poles. Its tensile strength is about one-half as great as that of copper; but its specific gravity is less than one-third (.3) as much, so that it has an advantage in this respect also. On the other hand, its diameter is 1.3 times that of an equivalent copper wire, so that it exposes correspondingly greater surface to wind surface and to the accumulation of ice. The electrostatic capacity of an aluminum line is higher than for copper of the same resistance and length on account of its greater diameter, as is evident from the formulae on pages 137 and 138. But the capacity being a logarithmic function of the diameter would not be much augmented by increasing the latter by 30 per cent. For example, the diameter of No. 1 wire is 42 per cent greater than that of No. 4 wire; but the capacity of a circuit composed of two of the former, placed 18 inches apart, is only 7½ per cent greater than if the latter were used. For overhead lines the electrostatic capacity of an aluminum conductor would not be more than about 5 per cent higher than that of an equivalent copper wire. Moreover, capacity does not play an important part except in very long transmission lines.

Aluminum is also a very suitable material for 'bus bars or other conductors that do not require to be *covered* with insulation; or in other words, *bare* conductors that are carried upon insulating *supports*, which applies to overhead lines as well. In such cases the fact that aluminum would have about 30 per cent more surface is an advantage in dissipating heat.

On the other hand, if aluminum conductors are to be *covered* with insulating material, as in the case of ordinary wiring in buildings, or especially with underground and submarine cables, then the fact that 30 per cent greater diameter and circumference are required is a disadvantage, since it increases the cost of insulation in about the same proportion. The lead covering or iron armor of cables would also be correspondingly augmented in weight and cost, and the space occupied would be greater to the extent of about 67 per cent in cross-section.

Sag and Stress in Overhead Conductors. — A wire suspended freely between two supports hangs in a curve called a catenary. The exact determination of the sag and other facts is somewhat difficult; but for electrical lines in which the sag is usually small compared with the span, very closely approximate results may be obtained by assuming the curve to be a parabola. A wire stretched between the points A B may be represented by the parabolic curve A E B. The horizontal distance A C B is called the span H in feet, the vertical distance D is the deflection or sag of the lowest point in feet, L is the actual length of the wire measured along the curve; T is the tension in pounds in the wire at its lowest point, and W is the weight of the wire in pounds per foot. We have the following approximate relations: —

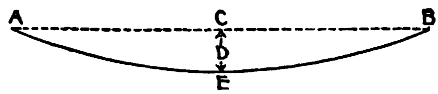


Fig. 182. Sag of Overhead Wires.

$$D = \frac{H^2 W}{8 T}, \tag{81}$$

$$T = \frac{H^2 W}{8 D}, \tag{82}$$

$$L = H + \frac{8 D^2}{3 H}. \tag{83}$$

With a given span H the tension T is a minimum when the sag D is one-third of H. In practice, the sag is made much less than this, being usually one to two per cent of the span, in order to avoid the strains and chances of making contact with other wires due to excessive swinging.

Expansion and contraction by changes of temperature produce considerable effect upon the sag and tension of overhead wires.

For this reason a greater sag should be allowed for wires laid in warm weather, in order to allow for the contraction in winter. The actual length L_t of a copper wire at a given temperature t in centigrade degrees compared with its length at 20° $C.$ is given by the following expression: —

$$L_t = L_{20}\,[1 + .000017\,(t - 20)] \tag{84}$$

The sag with the increased or decreased length may be found by solving (83) for D, which gives:

$$D = \sqrt{\frac{3\,H}{8}\,(L_t - H)} \tag{85}$$

The following table may also be used for determining the variations in sag, due to temperature changes. The sag in inches is given for every 10° between 30° and 100° F., being the limits between which lines are likely to be laid.

TEMPERATURE EFFECTS IN SPANS.

Spans in Feet.	Temperature in Degrees Fahrenheit. (Deflections in Inches.)								
	– 10°	30°	40°	50°	60°	70°	80°	90°	100°
50	.5	6	8	9	9	10	11	11	12
60	.7	8	10	11	11	12	13	13	14
70	1.	10	11	12	13	14	15	15	17
80	1.2	11	13	14	15	16	17	18	19
90	1.6	13	14	16	17	18	19	20	21
100	1.9	14	16	17	19	20	21	23	24
110	2.3	16	18	19	21	22	24	25	26
120	2.8	17	19	21	22	24	26	27	28
140	3.7	20	23	25	27	28	30	32	33
160	4.9	23	26	28	30	32	34	36	38
180	6.2	26	29	32	34	37	39	41	43
200	7.7	31	33	36	38	41	43	45	48

Hard-drawn copper wire, 60,000 pounds strength per square inch.
Stress at — 10° F., 30,000 pounds per square inch.

At —10° F. the sag is reduced, by the contraction, to the very small values shown in the table; and the tension in the wire is raised to 30,000 lbs. per square inch, which is rather too near the breaking stress, assumed to be 60,000 lbs. per square inch.

Hence it appears that the sag of about 1.7 per cent at 70° F., upon which the table is based, gives excessive tension if an overhead line, even of hard-drawn copper, is exposed to temperatures of —10° F. or less.

The *stretch* which occurs in wires considerably modifies the results obtained by calculations, using the ordinary formulae. This is particularly true of soft-drawn copper and aluminum, which show some permanent elongation with any considerable tension applied to them, and do not seem to have a definite elastic limit, like steel.

Poles. — In most cases wooden poles are employed to support overhead electrical conductors. But in some countries, notably in India, *iron poles* are used almost exclusively for telegraph and other electrical lines, because wood is rapidly destroyed by white ants. This is true of most other tropical regions. The form of iron pole generally adopted is hollow and tapering, being similar in its general size and proportions to the natural wooden pole, but somewhat smaller in diameter compared with length. It consists of sheet iron riveted together, and may be made in convenient lengths, the ends of which are fitted into each other. These set into a cast-iron base or sole plate, which is buried in the ground. In order to protect the iron, it should be galvanized inside and out, and should also be treated with some resinous material inside and outside, as far as it is buried in the earth. The insulators are carried on iron brackets, which are bolted to the pole, making a very strong and neat construction. In this country iron poles are made of sections of wrought iron pipe, with the joints either "swaged" or rusted. Sometimes for use as anchor poles, iron lattice construction is used.

Iron bases or sockets are often employed with wooden poles, enabling the latter to be made smaller in diameter and straighter. This also overcomes the objection to iron poles, due to the fact that they offer a ground connection to the wires or to the workmen, which in the case of the latter is very dangerous with high voltages.

Wooden Poles. — Chestnut is a very good material for this purpose, especially sawed or hewn for smaller poles. For large poles, pine is suitable on account of size and straightness; but pine, particularly southern pine and spruce, are not as durable as chestnut or cedar. The latter has long life, but is rather too crooked and

knotty for first-class work, where appearance is important. In California sawed redwood is recommended.

Preservation of Timber. — Wooden poles for electrical lines or other exposed timber is liable to be destroyed more or less rapidly by decay, or by the ravages of various small forms of animal life. The chief cause of decay is the fermentation of the sap. When located continually under water, wood is hardly affected by decay, but may be attacked by the *teredo navalis*, or other animal enemies. But when alternately dried and wet, or when buried in the earth, it is especially liable to decay. To prevent it various things have been tried.

1. **Kyanizing** consists in soaking in a solution of about three per cent corrosive sublimate ($Hg\ Cl_2$).

2. **Burnettizing** consists in impregnating timber with a 1 to 3 per cent solution of zinc chloride ($Zn\ Cl_2$), formerly by soaking, but now by forcing solution into the pores under pressure. Oak absorbs about 10 and pine about 20 per cent of its volume.

The trouble with the above processes is the dissolving out of the antiseptic salt, and various means have been devised to prevent it, such as the Thilmany process, in which zinc or copper sulphate solution was first forced into the pores and then barium chloride solution to form insoluble barium sulphate ($Zn\ SO_4 + Ba\ Cl_2 = Zn\ Cl_2 + Ba\ SO_4$). The Wellhouse process employed glue and tannin, and the Hagen process used gypsum to retain the salt in the wood.

3. **Creosoting** consists in placing the timber separated by laths on cars which are run into a large cylinder closed by heavy iron doors. Live steam at 225° to 250° F. is turned on until the timber is heated through, and the albumen of the sap coagulated. A vacuum is then formed to extract the sap, and finally the cylinder is pumped full of dead oil of coal-tar, a measured quantity being introduced under a pressure of about 100 lbs. per square inch. The amount of oil is generally from 10 to 20 lbs. per cubic foot of timber, the oil weighing 8.8 lbs. per gallon. Besides possessing antiseptic qualities, the oil is insoluble in water, and is not washed out or displaced by it. The oil usually only penetrates a little below the surface, hence this skin should not be removed by subsequent work upon the timber.

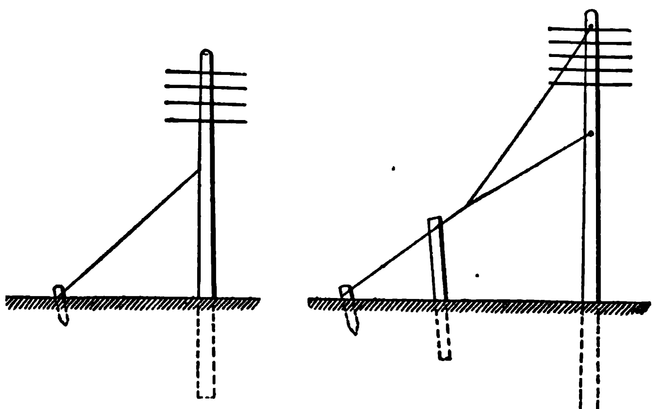
Creosoted telegraph poles in England showed no sign of decay

after 35 years.* In this country creosoted railway ties last about 20 years on the average. Cresoting also protects timber from the attacks of the *teredo navalis* and the *limnoria terebrans*.

4. **Carbolining** consists in treating timber at a temperature of 250° F. with an oil called *carbolineum avenarius* (invented by Captain Avenarius).

5. **Vulcanizing** is accomplished by heating timber in closed cylinders from 8 to 12 hours at 300° to 500° F., and under a pressure of 150 to 200 lbs. per square inch. A circulation of heated and dried compressed air removes moisture and any water that does not take part in the chemical reaction, and combine with the woody constituents. This process changes the character of the sap so that it does not ferment, and seals up the pores. Tests at Columbia University showed an average increase in strength of 18.9 per cent, in addition to preservative effect.

6. Applying *pitch* or *tar* to the butt of a pole may do more harm than good, as it confines the sap, hastening fermentation and decay. But, after the pole has been standing two or three years, it might be treated in this way, by digging around it.

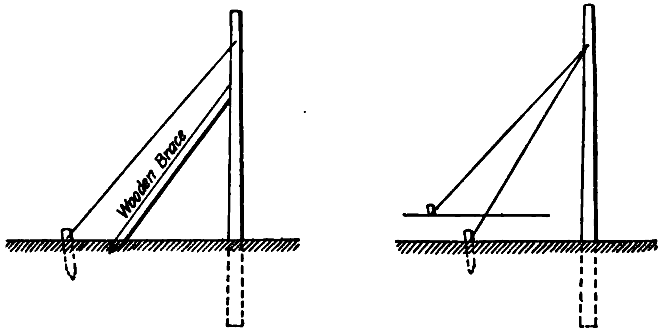


Figs. 183 and 184.

Poles are 35 to 60 feet long, but are sometimes 100 feet or even longer. Those of 50 feet or more are usually set about one-tenth of their length in the ground, but for shorter poles or in soft earth they are sometimes buried to the extent of one-eighth or one-sixth of their total length. In soft ground they should be

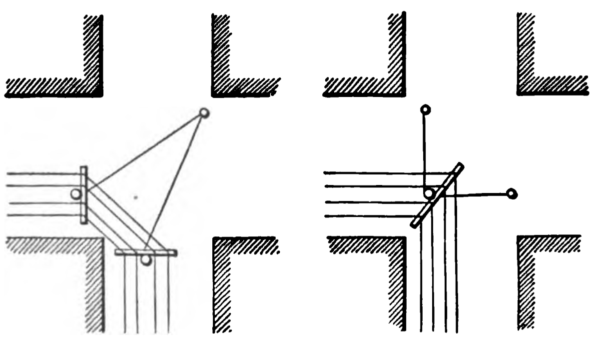
* N. W. L. Brown in *Elec. Railway Gazette*, October 19, 1895.

surrounded with a grouting of Portland cement, sand, and broken stone, tamped around the bottom of the pole, or the butt of the pole may be set in a barrel filled with sand or firm earth. The standard practice is to put from 40 to 50 poles per mile, making spans from 132 to 106 feet each. About every tenth pole should



Figs. 185 and 186.

be guyed laterally, to prevent wind pressure from overthrowing them. This is quite likely to happen; and if one pole falls it is likely to drag down the next one, and so on for a long distance, unless they are supported by side guys at reasonably frequent intervals. The guys usually consist of several strands of No. 6 or



Figs. 187 and 188. Arrangement of Guys for Turning a Corner.

8 iron or steel wire, which is more easily handled than the larger wire or rods that are sometimes used. They may be made simple, as in Fig. 183, or for high poles they have the Y form (Fig. 184).

Fig. 185 shows wire guy and pole brace. When a pole is to be made very secure it is guyed in two directions, or double guyed. This adds greatly to the stability of the pole. See Fig. 186.

On curves or at corners the guys should be more frequent and stronger, being placed on the outer side of the curve. Methods of guying suitable for lines that turn a right angle at street corners are shown in Figs. 187 and 188. In such cases, or where lines come to an end, as in front of an electric light station,

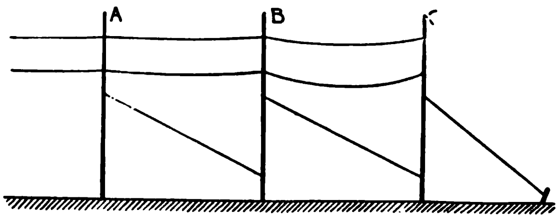


Fig. 189. Guying of Terminal or Corner Pole.

the last two or three poles should be stronger and more firmly set than the others, and may be guyed as indicated in Fig. 189. It is also well if the last one or two spans, A B and B C, are left somewhat more slack than usual, in order not to bring too much strain on the terminal pole.

Cross-Arms are of yellow pine or oak, being usually about $3\frac{1}{4} \times 4\frac{1}{4}$, or $3\frac{3}{4} \times 4\frac{1}{2}$ inches for smaller sizes, and as much as $4\frac{5}{8} \times 5\frac{3}{4}$ inches for the Niagara transmission line. A cross-arm about 3 feet long is used for two insulators, about 5 or 6 feet for 4 insulators, and so on. The spacing of the pins is about 4 to 6 inches from the ends, 24 to 30 inches in the middle, and 12 to 18 inches for the rest, depending upon the size of insulators and other conditions.

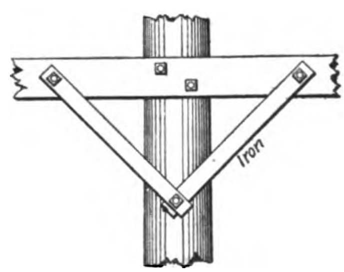


Fig. 190. Bracing a Cross-Arm.

The "gains" or flat spots on which the cross-arms are placed should be cut in the pole before it is set up. Ordinarily these are placed about 24 inches, center to center. The cross-arms should be fastened to the pole by two bolts or lag screws, placed diagonally in order not to split the wood, and are braced by two iron strap braces also attached by bolts or lag screws, as represented in Fig. 190. The cross-arms should be put alternately on opposite sides of the poles so that they cannot be pulled off successively.

Guard Wires. — Where one set of overhead electrical wires pass

under another set, the former should be protected by guard wires. An arrangement of this kind is represented in Fig. 191, *ABC* being the galvanized iron or steel guard wires attached directly without insulation to a cross-arm or to the top of the pole. These guard wires serve to prevent any wire that may fall from coming in contact with the electrical conductors carried on the insulators *DE*.

Guard Hooks. — A hook of stout iron wire or a hoop, as indicated in Fig. 192, is often attached to the cross-arm to catch an overhead conductor, and prevent it from falling in case the insulator, insulator pin, or tie-wire should happen to break. They are required especially on the inside of curves or angles in the line.

In this connection it may be stated that electric light or other conductors carrying high voltage or heavy current should, if possible, be put *over* telegraph and telephone wires, because the latter are more likely to fall, not being so well laid or so carefully watched,

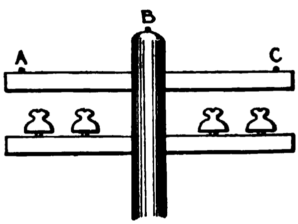


Fig. 191. Guard Wires.

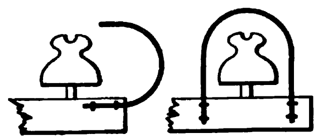


Fig. 192. Guard Hooks.

and being more numerous. Another reason for this is the risk of requiring telegraph and telephone linemen to pass up through the more dangerous wires with which they may not be familiar; whereas, electric light linemen would not be injured by telegraph or telephone wires.

Insulators. — The problem of supporting overhead wires is somewhat difficult, since those materials having sufficiently high insulating qualities are not very strong mechanically. Glass and porcelain are employed almost universally for the purpose, but neither is possessed of the great strength that is very desirable in order to enable the insulators to stand the heavy stresses to which they are subjected. Other materials, such as hard rubber and various compositions of vegetable or mineral matter, have been tried; but they are rarely used except that the latter are commonly employed to support overhead trolley wires.

The advantages of porcelain over glass are that it is less brittle and generally stronger than glass, and it is less hygroscopic. On the other hand, glass is cheaper than porcelain, and the fact that it is transparent enables an internal defect to be detected more readily. It also makes the cavities in the insulator less likely to invite the building of nests by insects. Another difference, which is much more serious than it sounds, is the fact that white porcelain insulators more often attract the eye of a boy or hunter, and frequently are made to serve as targets for stones or bullets.

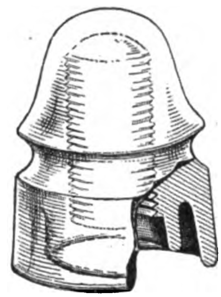


Fig. 193. "Deep Groove, Double Petticoat"; Screw-glass Insulator.

Glass or porcelain insulators for electric light and power lines have been developed directly from those that are employed for telegraph and telephone service. In fact, there is no substantial difference, the only modifications being an increase in size and strength to suit the heavier conductors, and improvement in insulation by lengthening the path for leakage of current, secured by adopting the double and triple in place of the single petticoat form.

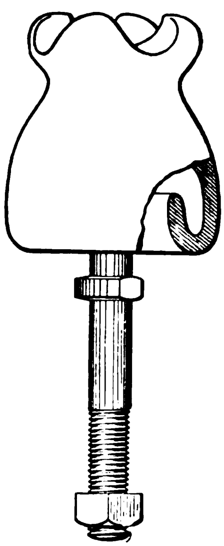


Fig. 194. Porcelain "Oil Type" Insulator, mounted on Iron Pin.

Types of Insulators. — The deep grooved double petticoat pattern of screw-glass insulator is the ordinary standard, being used with insulated wires for lines of 2000 volts. This type is shown in Fig. 193. For higher potentials the use of porcelain or special forms of glass begins.

The present increasing employment of high voltages, and the tendency to raise the voltage still higher, has brought into use new form of insulators.

The oil insulator, shown in Fig. 194, is mounted upon an iron pin, and provided with a recess that is filled with an insulating oil.

There is a "built-up" type of porcelain insulator, being made in parts as is shown in Fig. 195, and the parts burned together with a vitreous cement.

For 20,000 volts an insulator made entirely of porcelain was designed. Fig. 196 affords a very good idea of this type. In Fig. 197 is the porcelain pin base employed in combination with the insulator of Fig. 196.

The insulator used on the transmission line from Niagara to Buffalo, together with its wooden pin, and section of the cross-arm, is show in Fig. 198. The eaves tend to shed the water at two points, where it will not drip on the cross-arm.

An interesting insulator is the one used by the Telluride Power Transmission Company to transmit power 35 miles, from Provo to Mercur, Utah. The pressure, 40,000 volts, was the highest employed up to that time (1898) for commercial use. Fig. 199 shows the Provo insulator.

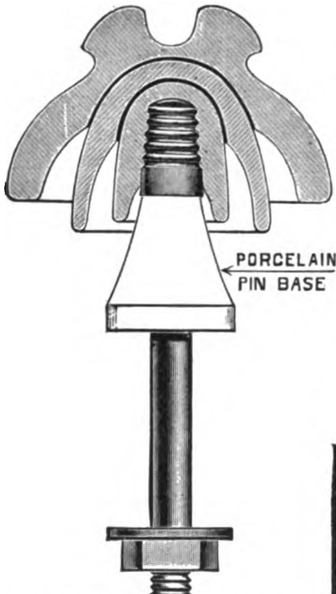


Fig. 195. Built-up Porcelain Insulator with Iron Pin.

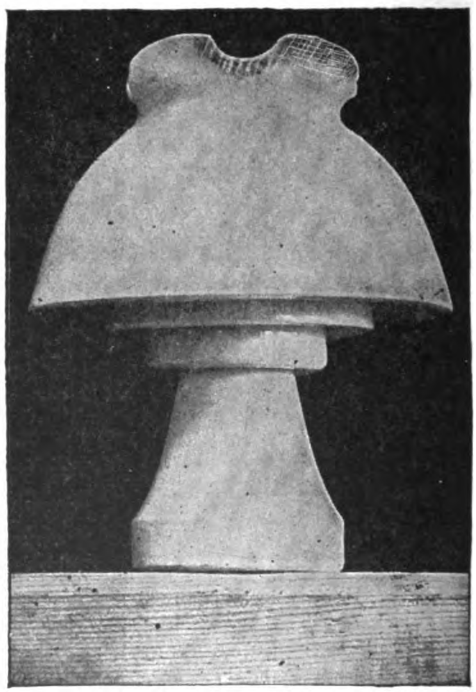


Fig. 196. 20,000 Volt Porcelain Insulator.

A still newer type is that shown in Fig. 200. It is of brown china ware with a glass or porcelain cone extending down around the pin, which is of wood with a porcelain sleeve and base. The idea of this sleeve is to make the striking distance

greater, this being of as much importance as that the length of the path from the cross-arm to the wire be made long. This insulator is $10\frac{1}{2}''$ in diameter, about $15''$ high, and weighs about 12 pounds.

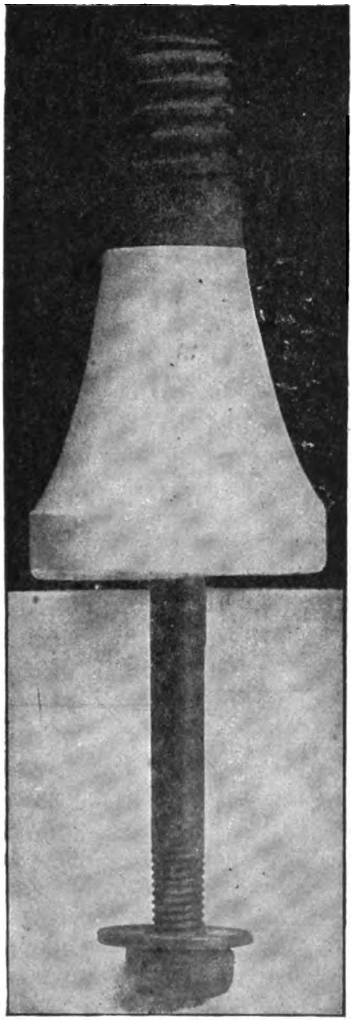


Fig. 197. Wood Pin with Porcelain Base.

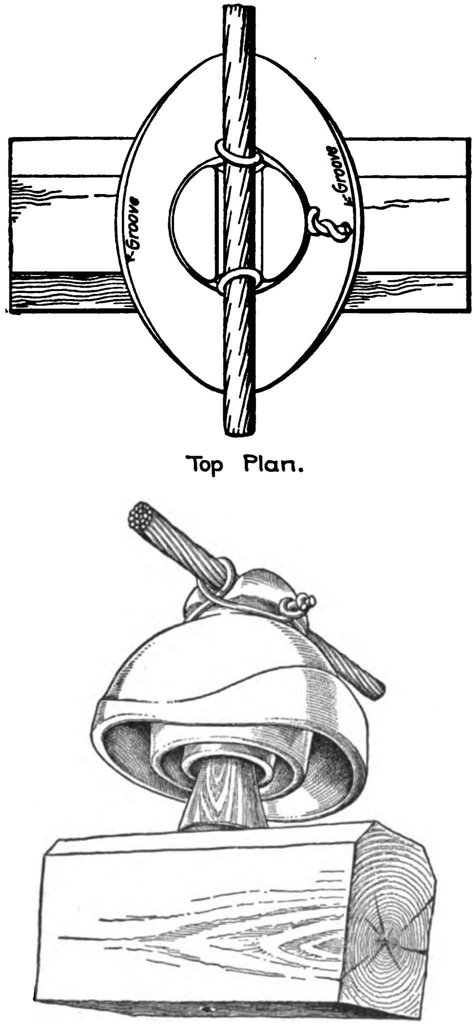


Fig. 198. The Niagara Type of Porcelain Insulator, Wood Pin and Cross-arm.

Another feature is the beveled trough around the top, which catches all the water at the periphery, and carries it off to one side of the cross-arm.

Insulated Wire for Overhead Lines. — For long-distance trans-

mission bare conductors, described at the beginning of this chapter, are generally employed, even with very high voltages. For local distribution, especially within the limits of cities and towns, electric light and power overhead wires are covered throughout with insulating material, to reduce the danger of accidental contact with persons or with other wires or conducting bodies.

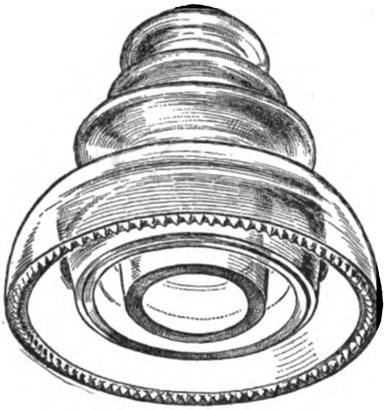


Fig. 199. Provo Glass Insulator.

The insulation of overhead wires is in two parts. One of insulating material impervious to moisture, placed next to the wire, and the other of some substance fitted to resist abrasion or like mechanical injury.

The inner coating is a rubber compound, or for lower grades some cheaper substitute. Before this is laid on the wire it is first tinned to prevent the sulphur contained in the rubber compound from corroding the wire. This inner coating is then covered with a hard braid of cotton or hemp, woven on to the wire, or the wire is served with a tape and insulating compound. Where the wire is to be continually moist, gutta percha is better than rubber, but it is more costly.

Fig. 200. Locke High Potential Insulator.

In the more expensive grades of wire the coatings are greater than two in number, and they alternate, insulating compound and then braid or tape.

In Figs. 201–203 are shown the manner of application of the insulation and the braid.

Joints in Overhead Lines. — Whether an electrical conductor is bare or insulated it is necessary that any joint made in it shall be nearly equal in conductivity and in mechanical strength to the

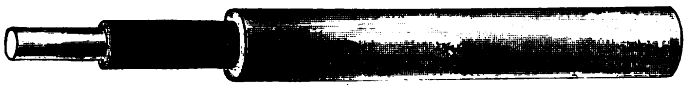


Fig. 201. Insulated Line Wire.

rest of the conductor. The ordinary "lineman's splice" (Fig. 204) has been the standard practice for galvanized wire iron, in telegraph lines; but the use of copper wire, both hard and soft drawn, and the necessity for better connection with heavy currents, has resulted in the adoption of various special forms of joint. Of these the McIntire joint illustrated in Fig. 205 is a prominent example.

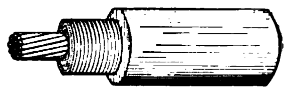


Fig. 202. Standard Conductor, Insulated for Outside Work.

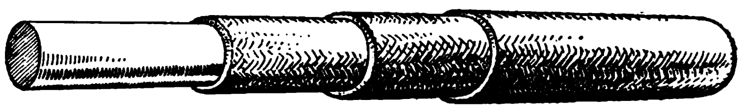


Fig. 203. Overhead Wire with Weatherproof Insulation.

This joint is made by use of a "connector" which consists of two tubes drawn side by side out of one piece of copper. The internal diameter of each of these tubes corresponds to the ex-

Fig. 204. Lineman's Splice.

ternal diameter of tne wire to be spliced. The two wires need not be of the same size.

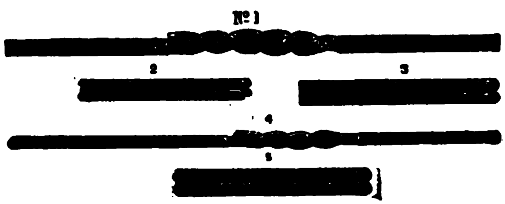


Fig. 205. McIntyre Wire Joint.

The joint is made by slipping the wires inside the tubes, and then by means of special pliers, twisting the tubes one on the

other; thus by friction the two wires are bound firmly together. Unless required by Insurance Rules, they need not be soldered, a great advantage with hard-drawn copper wire as it avoids annealing the wire, and the joint more nearly retains the full strength of the wire.

In the "lineman's splice" the actual area of contact wire to wire is small, and unless well soldered the crevices will afford places for starting corrosion, and the resistance will be high.

The McIntire joint affords plenty of contact area, giving a low resistance and being impervious to moisture. This form of joint is especially valuable with the aluminum wire that is now coming into use.

All joints made in insulated wire lines should be taped and painted with an insulating compound till the insulation over the joint is as good as that on the wire of the line.

Method of Attaching the Line Wire to the Insulators.—The ordinary plan is to take a simple U-shaped tie-wire, place the curve of it around the insulator, and wrap up the projecting ends around

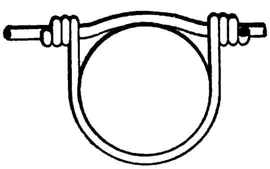


Fig. 206. Tying Wire to Insulator.

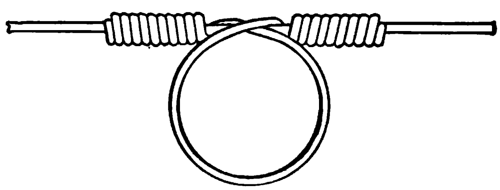


Fig. 207. Tying Wire to Insulator.

the line-wire. This puts a side pull on the line-wire which objectionable feature of this tie is indicated in Fig. 206. This might, in the case of hard-drawn copper wire, cause breakage, because it is quite brittle.

The standard method now in use is shown in a completed form in Fig. 207. A soft copper tie-wire is laid in and around the insulator groove, in such a manner that one end comes over, and the other end under the line-wire; the ends are then wrapped around the line-wire. A method of making the tie is shown in Fig. 208. When properly made in this way the line-wire is anchored to the insulator with no side pull.

Tie-wires should be the same size as, or slightly smaller than, the conductors themselves. This is true even when the line-wires

are insulated, and the insulation of the tie-wire should be equal in character and thickness to the line-wire that it ties.

Dead Ending. — When a line terminates it is dead-ended by taking a turn around the insulator and wrapping it about itself, or by means of a McIntire connector.

Service Connections and Loops. — When it is necessary to take a tap off to give service, an extra insulator must be mounted on the cross-arm, in order that the strain of the service main may not put a side strain on the line-wire; for a series circuit the line is usually dead-ended at the nearest pole, and a loop taken to the building to be served. In this case the arrangement shown in Fig. 209 may be used.

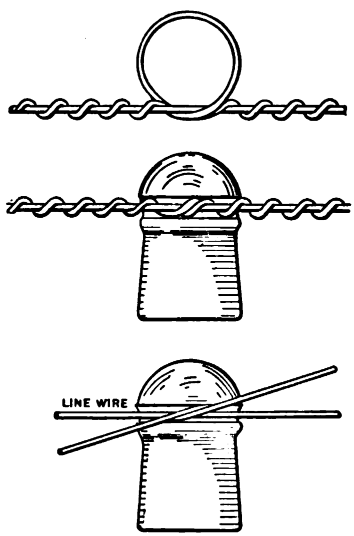


Fig. 208. Method of making Tie.

Limitations of Voltage. — The maximum voltage that it is possible to employ on overhead lines depends upon conditions. In 1890 a pressure of 5000 volts was considered to be very high, but gradu-

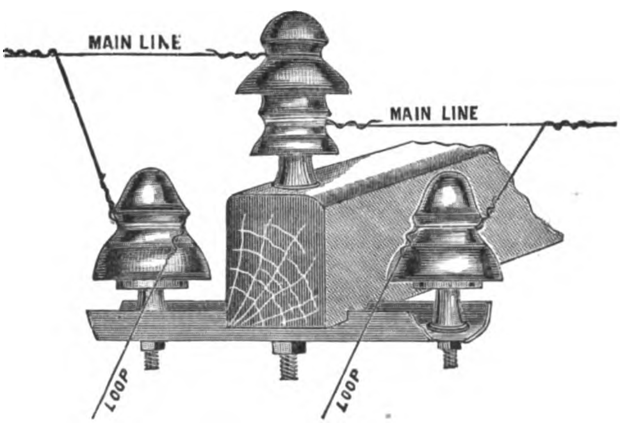


Fig. 209. Method of making Loop Connection.

ally the apparatus and methods have been improved until 40,000 or even 60,000 volts is now regarded as commercially practicable.

The electrical maintenance of such a circuit depends entirely upon the insulators, since the wires are usually bare, and the poles even if made of wood should never be depended upon for insulation, especially at such high voltages.

In a paper before the American Institute of Electrical Engineers,* Mr. C. F. Scott gave the results of experiments on several lines, and pointed out that the loss between wires by leakage directly through the air rose rapidly above a certain voltage. In Fig. 210, which shows some of these data, it will be noted (curve 1) that the loss between two No. 28 wires 48 inches apart was 500 watts at 30,000 volts, each wire being 1040 feet long. This is far too great for commercial work, since the waste would amount to about 2.5 k.w. per mile. With larger wires the loss decreases; for example, in curve 3 the leakage for two No. 8 wires the same distance apart is only one-fifth as great at 30,000 volts, being 100 watts for the same length. When No. 7 wires, rubber-covered, are used (curve 4), the loss is practically nil at 30,000 volts, and only becomes 50 watts at 60,000 volts, or .25 k.w. per mile. The substitution of still larger conductors secures a further reduction in this leakage through the air, so that it can be kept within reasonable limits even at 60,000 volts. A transmission line in California, which is designed to operate at this pressure, employs aluminum wires one inch in diameter, which should give very little air leakage, even though they are bare. When the distance between wires is increased, the loss is diminished, as shown in Fig. 211. It is also a fact that the leakage depends upon the wave form of the pressure, being greater with peaked than with flat topped waves, since the maximum volt-

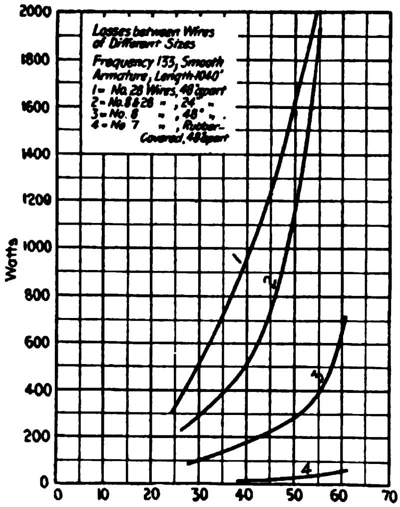


Fig. 210. Loss between Wires in Air.

* *Transactions*, June 30, 1898.

age is higher in the former case. The percentage of humidity in the atmosphere, or even a fall of rain or snow, does not materially increase this loss through the air.

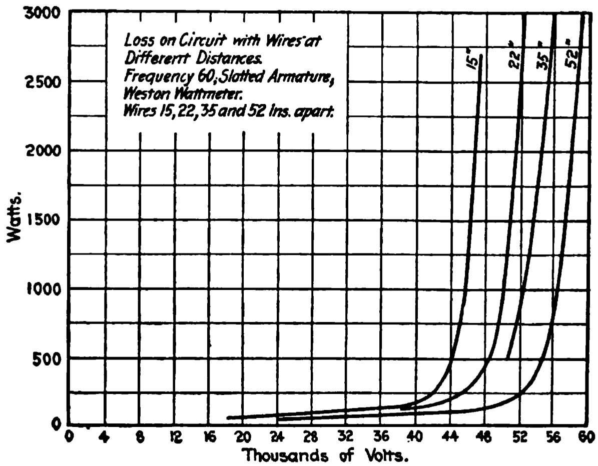


Fig. 211. Loss between Wires in Air.

Lightning Arresters are required in almost all cases in connection with overhead conductors. The principal forms in use, and the manner of using them, were described quite fully in Vol. I., pages 425 to 438.

GENERAL SPECIFICATIONS FOR ORDINARY POLE LINE CONSTRUCTION.

(2000 VOLTS.)

Poles to be of best quality cedar or chestnut, round or octagonal, as specified. Height to be approximately thirty (30) to thirty-five (35) feet. Diameter of base to be ten (10) inches. Diameter of top to be about six (6) inches. The poles to be straight and knots closely trimmed. Tops to be chamfered.

Gains to be cut square with the axis of the pole and with all other gains, and to be accurately made to fit cross-arms, so as to bring the cross-arms nearly flush with the pole.

Painting. Poles which are specified to be painted to have the lower six and one-half ($6\frac{1}{2}$) feet, including the base of the pole, either creosoted or painted with a heavy coat of tar paint or equal. (This is not to be done if the pole is "green" or sappy.) The roof of the

pole to be painted with three (3) coats of best quality white lead. All gains to receive two (2) coats of best white lead previous to the introduction of cross-arms. Lower shanks of pins to be painted with white lead before being inserted into cross-arms. Cross-arms to be thoroughly painted with two (2) good coats of mineral paint put on with a brush. After the poles are erected and wires in place all the poles specified to be painted with two (2) coats of best quality dark-green mineral paint.

Guy-Stubs and Anchor Logs to be used where the pole needs side guying on a sharp bend, or wherever the country does not provide a more convenient way to guy them. These anchor logs or guy-stubs to be of proper dimensions, depending on the size of the pole and weight of the line.

Cross-Arms to be thoroughly sound, straight-grained timber, of southern pine, and free from knots. The arms to be of requisite length, to be sawed true and square, and up to the dimensions specified. The top side of the cross-arm to be chamfered throughout the whole length, with the exception of eight (8) inches at the center, where the arm fits the gain. Cross-arms to have holes bored of spacing and size for pins, as specified or shown on drawings. Cross-arms to be screwed to the pole by two (2) $\frac{5}{8}$ inch galvanized iron bolts extending entirely through the arm and pole. Under the head and nut of each bolt a galvanized iron washer, not less than $2\frac{1}{2}$ inches in diameter, shall be placed. Bolts to be staggered. (This construction refers to cross-arms carrying heavy wires and large number of same. On light lines lag screws are sufficient.)

Iron Fittings to be of good quality best refined wrought iron, which would conform to good bridge specifications, to be thoroughly galvanized. Galvanizing to be subject to a test. Cross-arm braces to be used on all the cross-arms having four (4) or more pins. The braces to be secured to the pole with a lag screw, and to the cross-arm with carriage bolts of sufficient length to go through the braces and arms. Galvanized iron washers to be placed under the head of all bolts, nuts, and lag screws.

Pins. All pins to be best quality, sound, clear, split locust, free from knots and sapwood. Pins to be of standard dimensions, which are governed by the size and weight of the insulators, etc. The threading and tapering shall be neatly and accurately cut,

showing the full thread, and shall accurately fit the insulator. Each pin to be secured to the cross-arm by a sixpenny galvanized iron wire nail driven straight through cross-arm and shank of pin. On all curves pins to be bolted by galvanized iron bolts.

Insulators. Insulators as per sample to be used, to be sound, strong, free from fins, having threaded holes accurately molded and of uniform size. To be double petticoated, made of glass, and subject to a break-down test of 6000 volts, from a source capable of delivering five (5) amperes at that pressure.

Guy-Rods. Anchor guys shall be attached to galvanized iron guy-rods. These rods to be from 6 to 8 feet long, $\frac{5}{8}$ inch in diameter, provided with a galvanized iron washer $\frac{3}{8}$ inch thick and 3 inches square, with $\frac{3}{4}$ inch hole for reception of the rod.

Wire-Rope Fittings. All wire-rope fittings, such as thimbles, guy-clamps, rings, sockets, shall be of first-class quality of wire-rope fittings, equivalent in every respect to those manufactured by the Roebling Company or Washburn & Moen. To be galvanized.

Lightning Rods. Every tenth pole to be supplied with a lightning rod made of No. 6 galvanized iron wire, carried at least one foot above top of pole, and secured to same by heavy galvanized steel staples made of No. 4 (B. and S. gauge) wire. These staples shall be $2\frac{1}{4}$ inches long. The wire shall be carried down the pole, and thoroughly buried in the ground at the base of the pole, with at least two hand turns.

Guy-Ropes to be made of good flexible quality galvanized iron, and to be composed of one or more strands, depending on the stress to be borne by the guy. To conform to good specifications for elongation, twist, and breaking.

Construction Details. The line shall be located by measuring off and placing stakes for pole location at distances of 120 feet as an average. Such stakes must be placed as nearly in line as possible. In case of obstacles, the pole should be located as near the stakes as possible. In the distribution of the poles, the strongest and heaviest poles shall be placed on line corners, while the best-looking shall be distributed throughout the town, or in the front of residences. The length of the pole shall be proportioned to the contour of the country, so that the wires may be strung without abrupt changes in level.

On straight lines all poles shall be set in the ground to a depth

of at least six feet, unless otherwise specified. All poles shall be set perpendicularly on straight-line work. On curves, poles should be set with an outward rake.

The holes shall be dug sufficiently large to admit the butt of the pole without hewing; and after the pole is set, the earth shall be returned and thoroughly tamped around all the base of the pole. Tamping shall be done in the proportion of three tampers to one shoveler. Upon curves the poles must be laterally guyed.

Every eighth pole to be laterally guyed on both sides, and on steep hills every pole shall be head-guyed in both directions.

The two end poles of each line shall be head and laterally guyed. On long spans the poles shall be head-guyed both ways, and side-guyed in both directions.

"Y" guying to be used in all cases.

Where it is difficult to get good setting for a pole, same to be set in "sand-barrel" or concrete, to be approved by the engineers.

In cases where poles are set in rock, pole to be hewn to fit an approved iron shoe, which is to be securely bolted to rock. Shoe to be painted inside with two coats of white lead before pole is inserted. Outside of shoe to be smooth, and hydraulic cement to be placed on top of rock on which shoe is set.

Guys to be fastened to poles by means of galvanized eye-bolt, fitted with galvanized washers under head and under nut of bolt.

Placing of Cross-Arms. On straight-line work, the cross-arms to be placed on alternate sides of succeeding poles. On long spans the cross-arms of terminal poles shall be placed opposite the long section. Double cross-arms to be used on all abrupt changes in direction and also on end poles.

At the end of lines the arms of at least the last two poles shall be placed on the side facing the terminal of the line. On curves the cross-arms shall face towards the middle of the curve.

Long spans of 200 feet shall be head-guyed, and if possible side-guyed in both directions.

Tying of Wires. Line wires shall be tied in a manner as approved by the engineers.

Joints. All joints to be made either with a McIntyre sleeve or a Western Union splice, and to be thoroughly soldered, taped, and bound with cord.

Guard Hooks. To be placed on each cross-arm on sharp bends.

Guard Wires. To be placed wherever wires cross above or below another line.

Binding Wire. Binding wire to be used to secure wires on all insulators. Wires to be of first-class insulation, solid copper wire, two gauge numbers smaller than the line wire. No binding wire smaller than No. 8 B and S. gauge to be used.

Excavation. All excavating and filling for pole line to be done by contractor; also felling of trees, bushes, and all blasting, grading, etc. Trees and bushes to be trimmed so that no branch can come in contact with the wires. All removing and replacing of fences or other structures which may be found necessary for locating pole line to be done by the contractor.

CHAPTER XIII.

UNDERGROUND ELECTRICAL CONDUCTORS.

THE branch of electrical light engineering that is the greatest in magnitude, and involves the largest expenditure, is that which relates to the designing, laying, and maintaining of a large system of underground conductors. In no other department of electric lighting are the practice and results so variable. For nearly ten years after electric lighting was first introduced, the distribution of a current was effected almost entirely by overhead wires, the only important exception being the Edison Underground System, first laid in 1882, and generally employed by most of the low-tension, direct-current systems in the larger cities of this country, and in many places abroad. Since 1890 the popular objection to the use of overhead electrical wires has grown, and wherever possible has demanded the substitution for them of underground conductors. The enormous expense of making the change, as well as the almost utter lack of experience with buried high-tension circuits, made this a most formidable problem at first. As is usual in such cases, extraordinary methods were devised for overcoming the apparent difficulties. It has been found, however, that very simple construction, provided it is of good quality, insures the practical success and permanence of underground conductors. In fact, alternating current and arc-lighting circuits of 1000 to 7000 volts are commonly laid in underground conduits, and do not give much more trouble than low-tension wires, including those employed for telegraphic and telephonic purposes. The essential elements of an underground system of conductors are, first, the conductor itself, which is almost invariably composed of copper; second, the insulation, which may be either a complete covering of non-conducting material, or simply points of support; and third, the mechanical protection, which usually takes the form of a tube or conduit, and must be particularly strong in order to withstand the severe conditions to which it is exposed.

In some instances, especially in Europe, iron-armored cables are laid directly in the earth, without any conduit to protect them. The armor, which is relied upon for mechanical protection, consists of a spiral winding of iron or steel wire, like that of a submarine cable, or a spiral wrapping of iron or steel tape, with overlapping joints. In either case there is a certain amount of flexibility which a conduit does not possess, enabling the cable to pass around obstacles and adapt itself to the various underground pipes, etc., that are often very numerous in large cities. Moreover, the iron-armored cable would occupy much less space than an equivalent conduit. In some underground conductor systems the cables are drawn in after the conduits are built, and in others the conductors are put in the sections before they are laid, or are built in at the same time.

FORMS OF UNDERGROUND CONDUITS.

Drawing-In Systems.

IRON.

1. Wrought-iron pipes.
2. " " " cement lined.
3. " " " wood lined.
4. Cast-iron pipes.
5. " " troughs.

EARTHENWARE.

6. Terra-cotta pipes, single or multiple duct.
7. " " troughs " " "

CONCRETE.

8. One or more ducts formed in a mass of concrete.

WOOD.

9. Wooden pipes.
10. " troughs.
11. Fiber pipes.

Solid or Built-In Systems.

12. Edison and other underground Tube Systems.
13. Crompton and other naked Conductor Systems

Wrought-Iron or Steel Pipes, similar to gas or steam pipes with screw or other connections, is the strongest and one of the most satisfactory forms of conduit; and it has been extensively adopted,

particularly where its rather high first cost is not a serious objection. Its advantages are great strength to resist the severe strains due to the pressure of the earth, often aggravated by unequal settling. It is also well adapted to withstand blows of pick-axes, shovels, etc., to which conduits are exposed during subsequent excavations of the same ground. Wrought-iron or steel pipes require to be of less thickness, and therefore occupy less space than any other form of conduit. They can be joined by screw or other connections which are most secure, and can also be made water-tight. Such a pipe can be bent to a reasonable extent without breaking or opening the joints; whereas with almost any other form of conduit the unequal settling of the ground, which is almost certain to occur, is likely to crack or break it.

The disadvantages of wrought-iron pipes are their somewhat high first cost, and the fact that they are made of conducting material, which will cause a ground connection if the insulation of the wire is injured. It is doubtful, however, if non-conducting conduits, such as earthenware, are really better for underground construction. If a difficulty occurs in the insulation of the wire, the incidental insulation afforded by the conduit is hardly sufficient to enable the circuit to be worked properly. The moisture which would almost always be present would produce a sufficient "ground" to render it undesirable and probably dangerous to employ the conductor. In most cases it would be just as well, and would enable a fault to be more quickly detected and located, if a "dead ground," i.e., low-resistance ground connection were made immediately. In fact, with high-tension circuits in non-conducting conduits, it is important to have the lead sheathing of the cables that are ordinarily used well grounded throughout its entire length, otherwise a defect in the insulation, or simply the electrostatic charging and discharging which takes place with alternating currents, render it dangerous to touch the lead sheathing.

Wrought-Iron Pipe in Hydraulic Cement. — This is used to quite a large extent, the ordinary construction for this conduit consisting in digging a trench in the street, the size depending upon the number of pipes to be laid. The bottom of this trench, after being carefully leveled or graded, is covered with a layer of good concrete 2 to 4 inches deep, and the sides are braced with plank. A suitable mixture for this purpose is composed of

two parts of Rosendale cement, three parts sand, and five parts broken stone. Broken stone to pass through a one and one-half inch mesh. The concrete is well rammed into place, and a layer of wrought-iron pipe is laid upon it. The diameter of these pipes depends upon the size and number of cables that they are to receive, the standard being 3 or 4 inches in diameter, and ¼ inch thick. The pipes are in 20-foot lengths, and are joined by means of a tapering or vanishing screw thread coupling, forming a joint which is water- and gas-tight, and can easily be made as the pipes are laid in place. When the first layer of pipes is in place, spaces between and around them are filled with concrete. The distance between the pipes is usually one-half to three-quarters of their diameter, the thickness of the concrete on the sides being about the same amount. The concrete is filled in over the pipes to a depth about half of a diameter, and then another layer of pipes is laid and packed around with concrete as before. After the last row is in place, a covering of concrete from 2 to 3 inches in thickness is spread over it, and a layer of yellow pine plank 2 inches thick is laid upon this. The chief object of the latter is to serve as a protection against the tools of the workmen in case of later excavations. Experience has shown that men will dig down through concrete, but will turn aside from the wood.

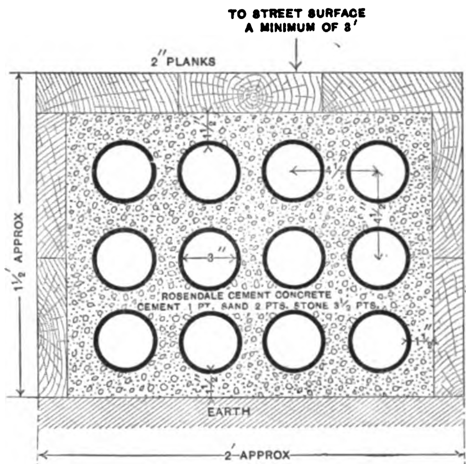


Fig. 212. Cross-Section of Iron Pipe Conduit.

The following construction is standard in this kind of work being used in New York City. (See Fig. 212.)

The thickness of cement all around the bunch of conduits is 1½ inches. The boards cn the side of the trench are 1½ inches, and there are 2-inch boards on the top. Three-inch wrought-iron reamed pipe is used, which is superior to the ordinary commercial pipe, in that it is reamed after being rolled to insure that there are

no blisters or rough points on the interior of the pipe. The pipe is dipped in a tar to prevent rusting. Fig. 212 shows a 12-duct construction. This is larger than the average.

The pipes are laid at 4½ inches between centers, both between the rows and the pipes in the rows. This adds up, for total conduit construction, about 1½ feet deep by 2 feet broad.

A cement formula that has been found sufficient is, Cement 1 part, sand 2 parts, and ½ inch broken stone 3½ parts.

It is evident that this construction is extremely substantial and well adapted to withstand the most severe mechanical forces, being also gas- and water-tight. The iron pipes are found to last very well, the action on their external surfaces being very slight. They rust internally to a considerable extent, being exposed to moisture and air; but it would take a long time for them to be corroded away entirely. Even should this occur, a smooth hole will be left in the concrete, and would still serve as a conduit for the conductors, and would last almost indefinitely.

The use of asphaltic concrete instead of that containing cement has been proposed; but it would be still more expensive, and would not seem to offer a compensating advantage. The manholes, handholes, and methods of distribution employed in connection with this form of conduit, will be described later, since they are quite similar for all types.

Wrought-Iron Pipes Lined with Wood have also been used; but, as already stated, it is doubtful if a non-conducting conduit is especially desirable. But the wooden lining would at least serve as a means of preventing the chafing of the cable as it is drawn in, and might in that way prove a valuable feature. On the other hand, it might tend to corrode the lead covering of cables as described later under "Wooden Conduits."

Wrought-Iron Pipe, Cement Lined.—This form of ducts usually consists of eight-foot lengths, made of thin (No. 26, B. W. G.) sheet iron, riveted every two inches, as represented in Fig. 213. The pipes are lined with a layer of pure Rosendale cement, ⅝ of an inch thick, no sand being used. The internal diameter is 3 inches, making the external diameter approximately 4½ inches. The outside of the pipe is tarred to prevent rusting. The interior surface of the cement is extremely smooth; in fact, it has a polished appearance, so that there is not an excessive amount of friction to

interfere with the introduction or withdrawal of the cables. Each section weighs between 40 and 50 pounds, and is therefore easily handled in laying and joining. These pipes are laid in cement in a manner similar to that described in the case of plain iron pipe, but the thickness of the pipes is somewhat greater. This form of conduit can be laid rapidly. Twenty ducts with a total of 12,820 feet of pipe were put down in a single day in St. Louis. The gang of men required to do this work were 36 concreters, 52 laborers, 6 bricklayers with 6 helpers, and 6 overseers. The trench in this case was already open; but the work included the

Fig. 218. Cement-lined Iron Pipe.

building of 1½ manholes and 4 handholes. In another case a gang of 108 laborers, 40 concreters, 5 bricklayers, and 5 helpers, with 7 overseers dug a ditch 1157 feet long, put in 5 ducts, and filled in the trench in a single day. These may be considered as extraordinary "runs," an average of 500 duct feet complete being the usual result of a day's work. Figs. 214 and 217 show conduits in course of construction.

Cast-Iron Pipe Conduit. — These are similar to the plain wrought-iron pipe already described. In order to have equal strength the cast-iron would have to be thicker than the wrought-iron, so that the cost would be as great or greater; and since the former occupies more space, and is heavier to handle, there is no great advantage in employing it. Cast-iron, however, lasts longer in the earth than wrought-iron.

Cast-Iron Trough Conduits. — Various forms of this construction have been used, a prominent example being the Johnstone conduit. This consists of shallow troughs of cast-iron in lengths of about 6 feet, which may be laid directly in the earth, as represented in Fig. 215. The cables are then run along in the trough, and covers of cast-iron are placed over the troughs, the two being bolted together. This construction possesses the advantages that the cables are laid directly in place without being drawn in, so that there is less liability of their being injured; and still more important is the fact that the cables are accessible at any point for

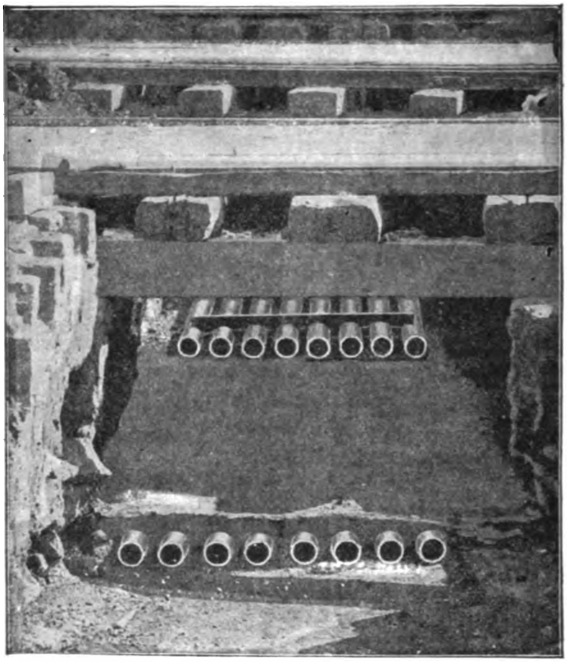


Fig. 214. Wrought-Iron Pipe Conduit in Course of Construction.

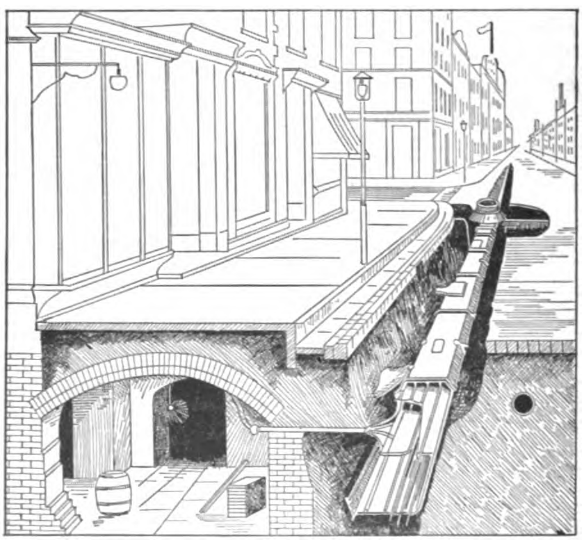


Fig. 215. Cast-Iron Trough Conduit.

inspection, repair, or branch connection, by simply removing one of the sections of cover, which are very easily unbolted and handled. For this reason the system is particularly well adapted to *distribution,* in contradistinction to transmission of current on feeders or trunk lines. Unfortunately the cost is so high as to be almost prohibitive. In some cases the troughs are completely filled with an insulating compound after the conductors are laid in them, thus excluding moisture, gases, chemical agents, etc., that might otherwise leak in and injure the insulation. Such construction, however, comes under the head of "built-in" and not "drawing-in" systems.

The self-induction of alternating current conductors laid in iron pipes or troughs must be overcome by twin or concentric cables.

Earthenware Conduits. — Various forms known as "terra-cotta," "glazed-clay," and "hollow-brick tile" conduits are manufactured and used. The ordinary single-duct form, illustrated in Fig. 216, consists of an earthenware pipe 18 inches long, the internal diameter being usually 3 inches, but smaller and larger sizes are made also. The thickness of the walls is about ⅝ inch, the external form being octagonal, as shown. These are made of clay burned moderately hard, and glazed inside and out. They are laid in a trench upon a bed of concrete from 3 to 6 inches thick, being placed side by side with spaces of ¼ or ½ inch between them, which are filled with cement mortar. Single-duct conduit joints being self-centering, are simply socketed one into the other. The conduit is built up in layers, with the pipes breaking joints very much like the bricks in an ordinary wall. The concrete consists of 1 part cement, 2 parts sand, and 5 parts screened gravel, broken stone, or broken brick; the stone to pass through 1½-inch

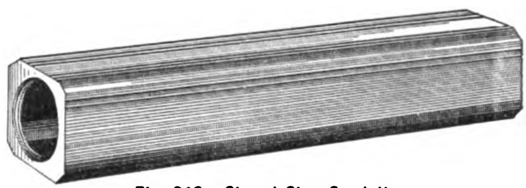


Fig. 216. Glazed Clay Conduit.

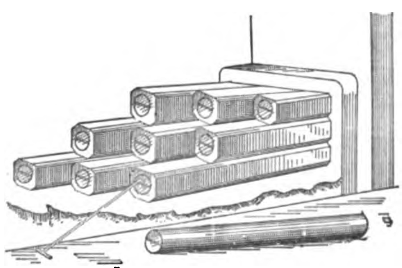


Fig. 217. Glazed Clay Conduit.

mesh; the cement and sand to be first thoroughly mixed dry, then a sufficient quantity of water added to make a rather soft mortar; the gravel, stone, or brick to be added afterwards, and thoroughly mixed. The gravel, stone, or brick should not exceed one inch in its greatest diameter. The conduit is usually protected on the sides and top by a layer of concrete at least three inches thick; but in some cases the concrete is omitted, when two one-inch yellow pine boards are placed over conduit. Great care should be exercised in laying the ducts so that the alignment is sufficiently good to enable the conductor to be easily drawn in and without injury. This is generally secured by inserting a round stick or mandrel of wood through the ducts as they are laid. The mandrel, which fits

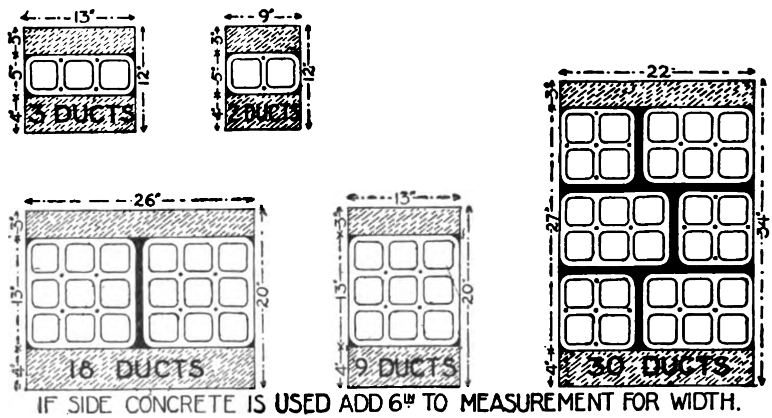


Fig. 218. Multiple-duct Earthenware Conduits.

the bore of the pipes quite closely, insures that they are in line while being filled around with mortar, and there is a disk of rubber on the end of the mandrel that acts to scrape out any mortar or dirt that may happen to get into the duct. The axis of each pipe is slightly curved, and they should be laid so that the convex side is upward, in order that the joints shall interfere as little as possible with drawing in the cables. The advantage of this form of conduit is its simplicity, cheapness, and the fact that any desired number of ducts may be put together; and to avoid obstructions underground, the geometrical form of the conduit may be modified by different arrangement of the separate pipes, and it is quite easy to slightly change its direction, so that it may be carried around obstacles.

Multiple-duct earthenware conduits are similar in general form and method of laying to the single-duct construction just described. The difference lies in the fact that each unit contains two or more ducts, as represented in Fig. 218. In this way space and the labor of laying are somewhat economized. Multiple-duct conduits are centered with two dowel pins at each joint, and then wrapped with

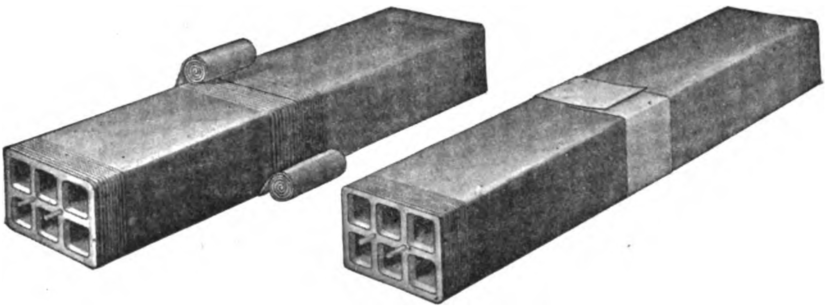


Fig. 219. Joints in Multiple-duct Conduits.

a six-inch strip of asphalted burlap, or with a six-inch strip of damp cheese cloth, and then given a coating of cement mortar, as shown in Fig. 219.

Earthenware Trough Conduits consist of clay troughs, either simple or with partitions, as represented in Fig. 220. The usual dimensions are 3 or 4 inches square for each compartment, with

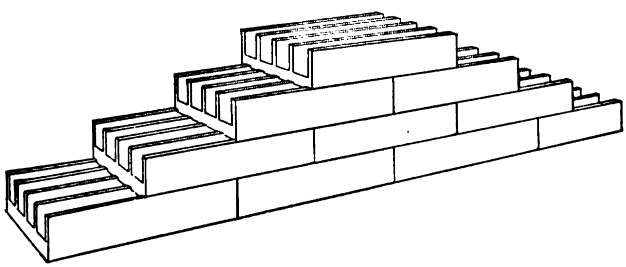


Fig. 220. Earthenware Trough Conduits.

walls about 1 inch thick, the sections being 2 to 4 feet long, and weighing about 85 pounds each for the 2-foot four-duct trough shown. To cover the top trough a sheet of mild steel, No. 22 gauge, is bent to fit over the sides to hold it in place, and is covered over with concrete. When the latter has solidified, it acts as a roof to the top layer of ducts, even though the sheet of steel rusts entirely away.

Ducts formed in Concrete. — A method of constructing a conduit consists in partly filling a trench with concrete in which continuous longitudinal holes are formed to serve as ducts after the concrete has hardened. One plan is to use collapsible mandrels of wood or metal, which are placed where the ducts are desired and then filled around with concrete. When the concrete has solidified the mandrels are made to collapse, and taken out in pieces. Another means of producing a similar result is to employ tubes made of thin sheet zinc or iron, which are placed in the concrete as it is filled in, and are just strong enough to stand the pressure to which they are subjected. It is expected that the thin metal will soon corrode away, but the ducts will remain in the mass of concrete.

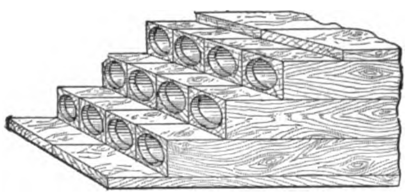


Fig. 221. Wooden Pipe Conduit.

Wooden Pipe Conduit. — A simple and cheap form of conduit consists of pieces of wood 3 to 6 feet long and 4½ inches square, through which a round hole 3 inches in diameter is bored longitudinally. These are laid side by side in layers, as shown in Fig. 221, to form a conduit with any desired number of ducts. At the bottom and top a layer of plank is laid to protect and hold in place the separate pieces. There is a projection at one end of each section which fits into a corresponding recess in the next section, as indicated in Fig. 222. This conduit is often called *pump-log* conduit.

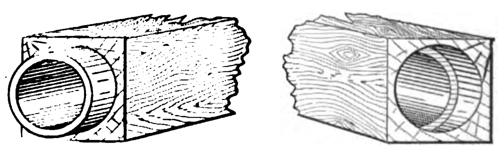


Fig. 222. Wooden Pipe Conduit.

Wooden Trough or Box Conduit. — Ducts about 3 inches square are made of horizontal boards and vertical partitions of yellow pine one inch thick. This may be laid in convenient lengths of about 12 feet or may be built along continuously. The wood should have been previously treated with creosote or dead oil to preserve it, as described on page 244, and the whole exterior of the conduit is coated with tar.

The objection to this or any form of wooden conduit is the

fact that the decay of the wood tends to form acetic acid which attacks the lead sheathing that is usually applied to underground conductors. This produces a white scale, irregular pits, or a white efflorescence on the lead, and is likely to cause much more damage than the dark brown uniform coating which sometimes forms on lead but stops further action. The lead acetate resulting from the first-described action is often decomposed by carbonic oxide changing it to lead carbonate, and setting free the acetic acid which again attacks the lead and so on. The decay of the wood and formation of acetic acid are intended to be prevented by the treatment with creosote or dead oil, but this may not be entirely effective. Wood is good for temporary work, for it will last about 10 or 15 years, and can be easily cut into for changes and repairs or side connections.

Fiber Conduit consists of pipes made of wood pulp, having about the same thickness as cast-iron pipe. *Slip* joint conduit for electrical subways is 3 inches inside diameter, and has short sockets on the ends, one to fit inside the other, keeping the lengths centered, and making it much easier to lay than a mere butt joint. It is laid in cement like iron pipe. The *screw joint pipe* will form a tight line, and is used for running underneath the lawns of private houses, or underneath the streets of villages, the importance of which will not warrant the cost of building electric subways. Being used in this manner like iron pipe, it can be cut with a saw or lathe tools. It is said not to corrode nor change in dimensions with varying temperature.

Ordinary conduit construction is illustrated in Fig. 223, the conduits in this case being terra-cotta, but may consist of other kinds of pipe.

It is hardly necessary to lay conduits below the frost line as they are not likely to be injured by frost. When laid in concrete they should be at least 2 feet below the surface, and when clay pipes are laid bare, 3 feet, to avoid crushing by the weight of the heavy vehicles above.

Edison Tube System is a very good one for distribution, and for extending to new territory section by section, being much more convenient in this respect than conduit and cable.

The *Tube* consists of one or more conductors contained in and insulated from an iron pipe. In the three-wire system which is in

general use, three copper rods are placed in each tube. The system is a sectional one, and each tube is as complete when it leaves the factory as is a rail from the rolling-mill. Like a rail it only needs to be joined to other similar units to become part of a continuous line. These tubes may make as many bends as circumstances call for, while a conduit must run practically straight from manhole to manhole.

In the three-wire system of distribution the conductors, whether overhead or underground, are divided into two classes. *Feeders*

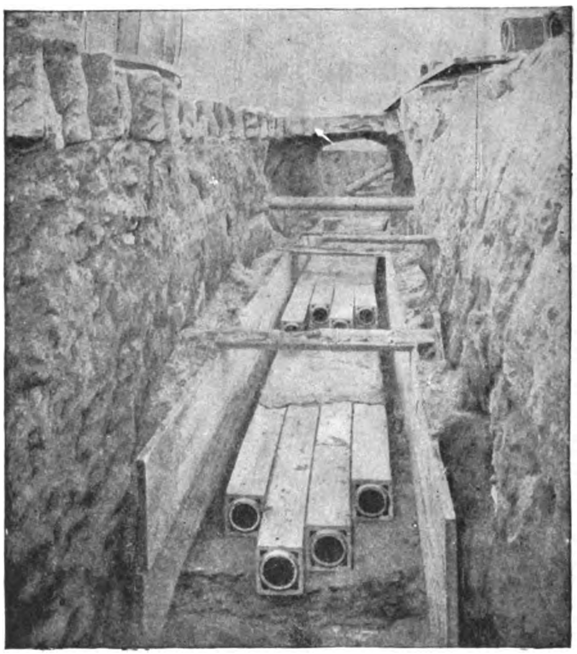


Fig. 223. Terra-Cotta Conduit under Construction.

which run from the stations to the centers of distribution constitute the first class. *Mains* radiate from centers of distribution, and loop the ends of the feeders together, constituting the second class. All taps to supply customers with current are taken from the mains. Tubes are therefore divided into Feeders and Mains. A main has three insulated conductors of the same size. A feeder has two principal conductors and a smaller conductor to serve as a neutral wire. A feeder also has three insulated cables of 7 strands

of No. 19 B. W. G. wires each. These small cables form independent circuits from the station to the point of distribution, and enable the voltage at the outside end of the feeder to be read in the station. Hence these lines are called pressure wires. See Fig. 227.

The conductors are all copper rods, 20 feet, 4 inches long, and project from 2 to 3½ inches from each end of the pipe. The pipes are lap-welded steam pipe, of full weight.

In making up a tube the ends of the copper rod are first chamfered and tinned. The pipe is thoroughly cleansed on the inside. Each rod is wound separately with a prepared rope, and the three rods so wound are made into a triangular bundle and

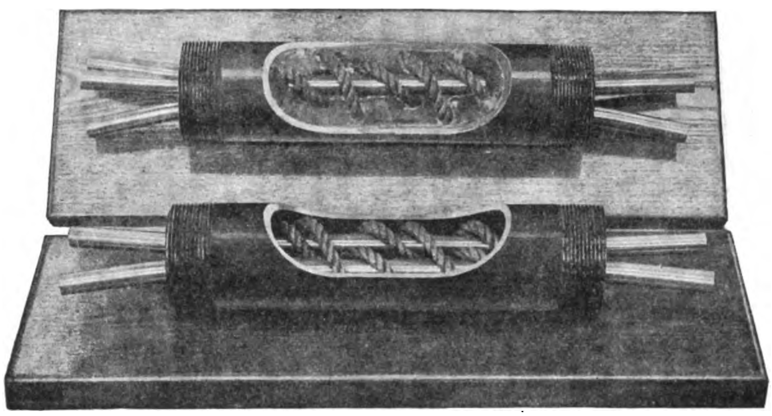


Fig. 224, Construction of Edison Tube.

wrapped with a fourth rope. See Fig. 224. This bundle of rods bound with rope is slipped into the pipe. When the rods are in position the pipe is placed on end, and a melted special compound is forced in from the lower end. As the compound rises it displaces the air, and thus prevents air bubbles. The ends of the pipe are closed with a rubber plug. As soon as the insulating material is cooled the completed section of the pipe is carefully tested, the tube is then painted to preserve the iron from rust, and is ready for shipment.

In order to complete the system, there is needed a means of joining the ends of the conductors in the consecutive tubes, and of insulating and protecting such a joint when made.

In Fig. 225 it will be seen that the two ends of the pipe enter an egg-shaped casting through two water-tight sleeves at either end of the oval. The copper rods forming the conductors are joined by coupling joints consisting of short pieces of flexible cable with sockets cast on each end. These sockets are drilled to fit easily over the rods which the joint is to connect. After the connectors are in place they are thoroughly soldered to the ends of the conductors, thus making an electrical joint. The covering of the egg-shaped casting is bolted down on the lower half, and by means of a small hole on the top of the casting, the whole of the box is filled with melted insulating compound, which surrounds and insulates the copper rods, the joints and the tube ends. This

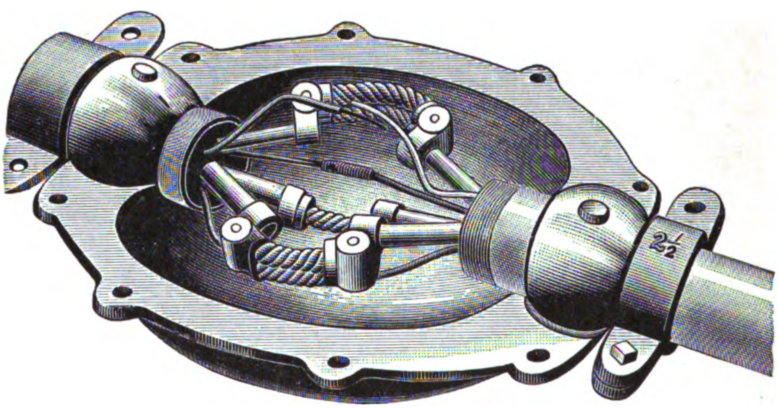


Fig. 225. Coupling for Edison Tubes.

compound does not grow brittle on cooling or with age, but remains somewhat plastic even at freezing temperature. The hole in the casting is closed with a cast-iron cap.

Coupling-boxes are made also in the form of elbows and tees, to provide for all possible conditions, such as service wires, turns in the line, etc. The ball end that may be attached to the end of the tube, and the socket that it fits into, permit a considerable variation in direction if desired, there being a range of 18 degrees on either side of the mean position.

Branches to the consumers' premises, or as they are commonly called the *services*, are short lengths of tube which tap the main line by means of a three-way or service box. These boxes are made for right and 45 degree angles. A four-way box readily per-

mits of two services being taken from one joint. A form of box is shown in Fig. 226.

Mains are so placed in the ground that the positive and negative conductors are on one side of the vertical plane through the

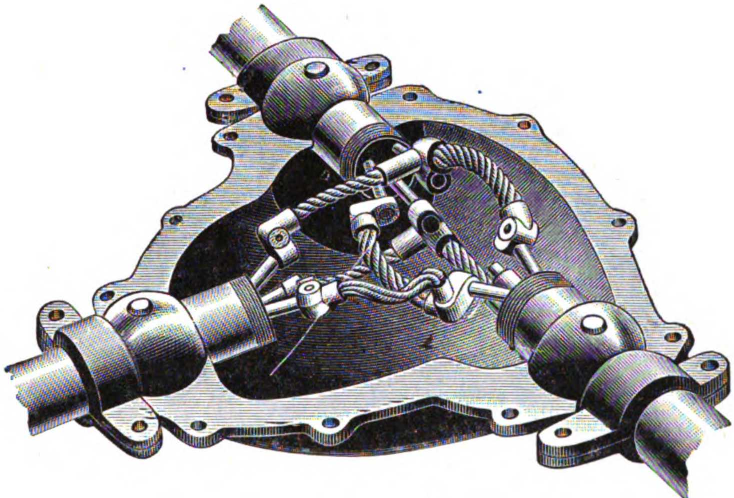


Fig. 226. Branch Connection of Edison Tubes.

center of the tube, while the neutral or balancing wire is on the other. See Fig. 227. The side of the tube which the neutral is on is called the inside, because the main tube is so placed that the neutral copper is nearer to the curb line. The feeders are laid symmetrically, with the right hand conductor as the tube leaves the station being the positive. Services are never taken from the feeder-lines. This requires that

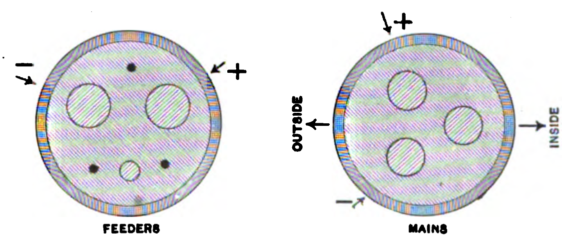


Fig. 227. Cross-Section of Edison Tubes.

at some center of distribution the feeder be split up and branched out, or what is the same thing that it be connected up to one or more mains. The feeder enters a distributing-box, and the conductors are connected to three copper rings. From these rings, as a source of potential, mains are led out through fuses to supply, by

means of the service connections, the surrounding district. From the rings of this box the pressure wires return to the station. This box not only serves as a center of distribution, but also as center of equalization of pressure between the different parts of the system. Fig. 228 shows the arrangement of the distributing-box. In some cases the fuses are replaced by heavy copper strips.

Installation of the Tubes. The trench in which the tubes are to be laid should be as a rule 30 inches deep, and 20 inches wide

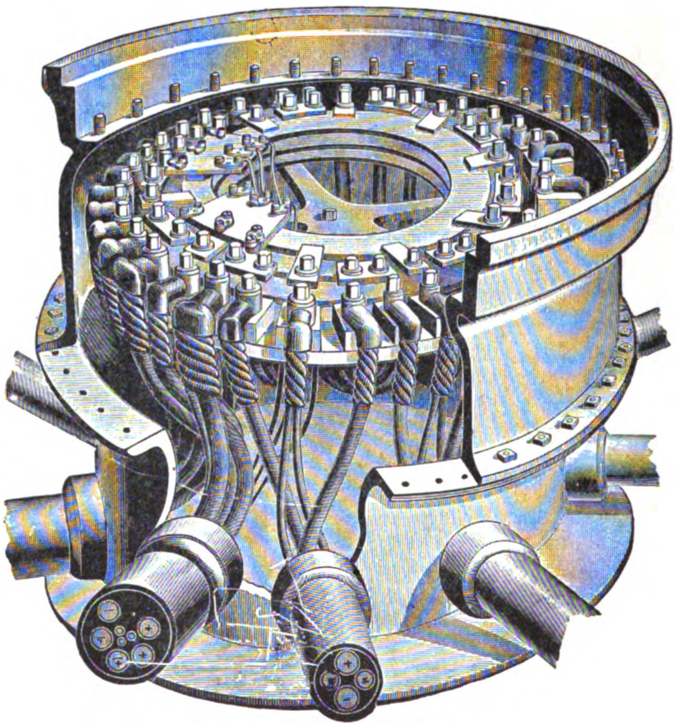


Fig. 228. Distributing Box. Edison Tube System.

at the bottom, this giving a trench wide enough for two tubes. As is shown in Fig. 229, the main is laid nearer the curb to facilitate the taking off of taps or services to the houses; such services running under the sidewalk, and entering the cellars of the houses. If there is only one line of main on a street, it is laid about six inches higher than the feeder, should there be one, in order that services may be taken off for both sides of the street.

The system may seem burdened with details; but when it is

considered that the system takes the current from the dynamo, and delivers it to the consumer, that the tube is the equivalent of three ducts in a conduit and three insulated cables, and that its flexibility is great, we see that it possesses advantages. For many years it was the most important underground system.

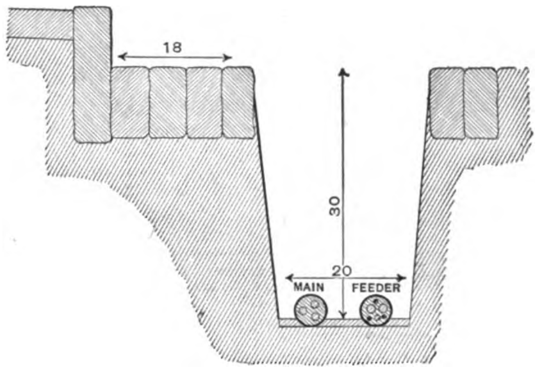


Fig. 229. Edison Underground Tubes.

Naked Conductor Systems.—There are at least two methods by which bare wires or rods may be operated in underground conduits. One in which the wires are supported on insulators of glass, porcelain, soapstone, etc., in the conduits; and the other in which the conduit itself is of an insulating material.

The former method is used somewhat extensively in Europe, entirely, however, for low pressure electric lighting service.

In this use of bare conductors care must be taken to prevent the undue access of moisture into the ducts, and especially to prevent the flooding of the conduits.

The Crompton System of bare copper strips has been extensively used in England. The conduit, or culvert for a three wire system is shown in Fig. 230, and will be seen to be a trench lined with concrete, and covered with a layer of flag stone. It is usually built under the sidewalks. The conductors are copper strips 1 to $1\frac{1}{2}$ inch wide, and $\frac{1}{4}$ to $\frac{1}{8}$ inch thick.

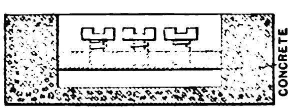


Fig. 230. Crompton Conduit.

These strips rest in notches on the top of the porcelain or glass insulators, which are carried on an oak timber built into the concrete walls.

To prevent the leakage from moisture it is necessary that the number of the supports of the strip be reduced to a minimum. To accomplish this, about every 300 feet there is an enlarged handhole for a straining device which takes all the sag out of the

strips, and makes it possible for them to place the insulators about 50 feet apart, instead of every 10 feet. This device is shown in Fig. 231. The conductors are, when stretched, clamped by the set screws W. The ends of the strips are then joined by the clamp C.

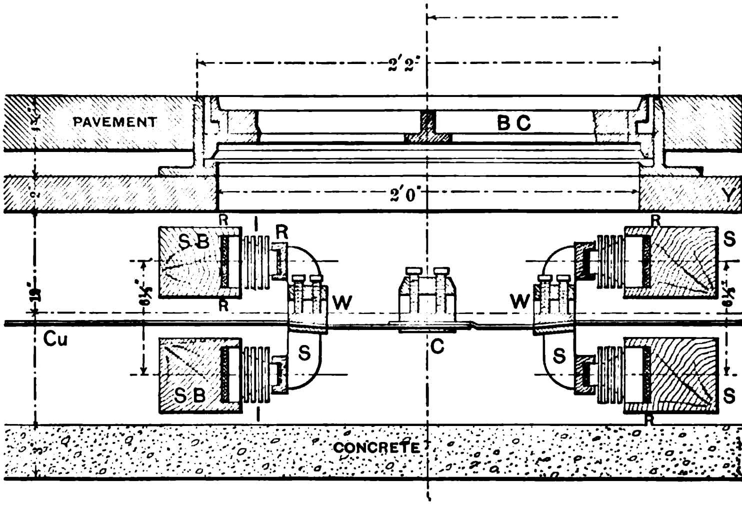


Fig. 231. Stretching Device in Crompton System.

In order that the insulators may be reached for inspection and for cleansing, a hand-hole is placed over each set of insulators, — that is, about every 50 feet, — and these boxes are utilized for the service connections. Rubber-covered cable is generally used for this service, and it is attached to the copper strips by a clamp like C in Fig. 231.

The Kennedy System is a modification of the Crompton, using solid porcelain bench-like supports set directly on the bottom of the conduit, as shown in Fig. 232.

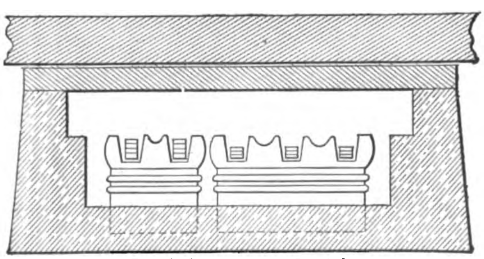


Fig. 232. Kennedy Conduit.

The Callender Solid System. In the Callender solid system a series of cast-iron troughs are laid along the bottom of a trench excavated in the street. In the trough the requisite number of

cables are strung, supported at intervals by insulating pieces fixed in the troughs. This protection is found to be necessary, from the fact that the insulating compound with which the trough is to be filled is never absolutely hard, but behaves like a viscous fluid; and the cables would otherwise gradually settle.

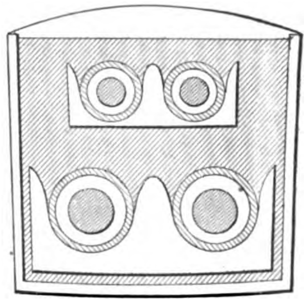


Fig. 233. Callenaer Conduit.

The cables are insulated, and with the melted asphalt that is poured into the troughs, makes an expensive insulation. A cast-iron cover is placed over the top of the trough. A section of this system is shown in Fig. 233.

Electric Light Cables for use in conduits are of two classes, according as the insulation is or is not moisture proof. In the first class the insulation is rubber, or bitumen, and the lead covering is for the protection from chemical and mechanical injuries. The second class is insulated with jute, hemp, or paper impregnated with oil, wax, or resinous compound. The lead covering of this cable is absolutely necessary for its electrical integrity, on account of the hygroscopic nature of the insulation. The latter types are much cheaper, but need the test of time to demonstrate their value.

Rubber is made durable and the cost reduced by being compounded with litharge, French chalk, barytes, etc., which strengthen it mechanically, and render it less liable to decompose.

Vulcanized rubber is now generally used, it being mechanically stronger, more flexible, and capable of standing higher temperatures than pure rubber. The process consists in mixing a small amount of sulphur with the rubber, and subjecting it to a temperature of 250 to 200 degrees F., while keeping it under pressure.

Fearing the action of the excess of uncombined sulphur on the copper, the conductor is tinned before the insulation is applied. It will be seen that for a cable of many strands the wires themselves must be tinned. The Hooper process may be applied, consisting in first covering the cable with a layer of pure rubber, and then with a layer of rubber highly pigmented with oxide of zinc, and then to put on the vulcanized rubber. The requisite amount of sulphur can be determined so closely that the excess may be very small, so that this separating layer may not be necessary.

The general method of insulating a cable is to first wrap round it one or more layers of pure rubber tape, which are put on spirally; the direction of the spiral being reversed for each successive layer. On top of this, rubber compound is applied in two or more separate coatings, each coat being put on by passing the partially formed core with two strips of rubber compound, one above and one below it, between a pair of rollers which fold each strip half around the core, and press the edges of the two strips together so as to make a

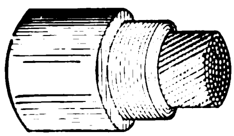


Fig. 234. Lead-covered Stranded Cable.

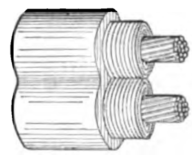


Fig. 235. Duplex Cable with Fibrous Insulation.

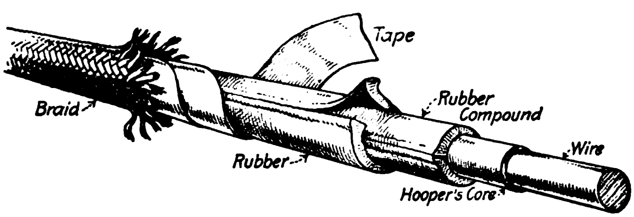


Fig. 236. Underground Cable.

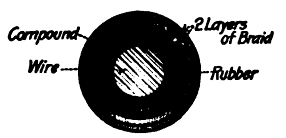


Fig. 237. Underground Cable.

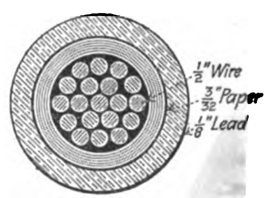


Fig. 238. Underground Cable.

good joint along each side. When a sufficient number of layers of rubber compound have been put on to give the requisite thickness, the core is tightly bound with a spiral wrapping of prepared rubber tape, and then vulcanized. After this it is tested; and if it proves satisfactory then it is taken to the taping and braiding machines, where the external covering of tapes and braiding is put on.

Lead covering. These cables are generally incased for their mechanical protection. This may be done by drawing the cable into a lead tube, which is then drawn through a die and made

to fit the core tightly; or the lead cover may be put on in a hydraulic press, the hot lead being forced out through an annular die around the cable.

The Siemens cable is one of the second class, the conductor being wrapped with jute, and impregnated with a special bituminous compound mixed with heavy oil, and is then covered with lead.

Paper cable. A similar cable is of paper wound on in strips spirally over the conductor; and as each strip is applied, it is passed through a die which presses it into a compact mass. The core is then dried at a temperature of 250° F. to expel the moisture from the paper, and immersed in a bath of compound, from which it passes directly to the lead-covering press.

With either of the methods of lead covering by a press, it is difficult to test the soundness of the lead, unless the cable is immersed in water for a long time. For this reason some makers prefer to use a manufactured lead tube, which can be tested under pressure to see if it is sound, and then the cable is drawn into it.

Figs. 234 to 238 represent the general form of cables.

As one type of special cable, Fig. 239 shows a lead-covered, three-conductor cable, such as is being used for three-phase transmission of current at 6600 volts, from the 96th-street station to various sub-stations in New York City. The conductors are each equivalent to a No. 0000 A. W. G. wire, and are composed of thirty-seven strands of tinned Lake copper. Around each conductor is a Hooper core containing no sulphur; the total insulating wall around each conductor is $\frac{6}{32}$ of an inch. Together with the jute fillers these conductors are twisted with a lay of about 20 inches. The whole is then covered with a second insulating wall of $\frac{4}{32}$ inches' thickness. Lead covering $\frac{1}{8}$ inch thick is then put on. The covering is an alloy of lead and tin, the percentage of tin being $2\frac{1}{2}$ to 3. The total diameter of this cable is $2\frac{3}{8}$ inches.

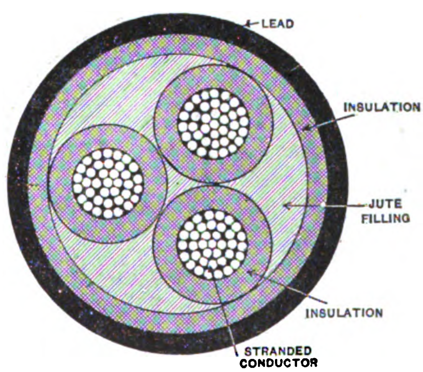


Fig. 239. Three-phase 6600 Volt Cable.

This iorm of insulation is popularly called *split insulation* for the reason that it is substituted for a cable having $\frac{10}{32}$ of an inch around each conductor, and none around the bunch of three. Should the latter form of cable be used, it would perhaps be one quarter inch greater in diameter, and would cost at least 25 per cent more. The "split insulation," it will be seen, offers the thickness ($\frac{10}{32}$) of insulation needed between conductors, and the same thickness between conductors and the lead sheath as in the old style.

Each individual conductor before assembling is tested, after 24 hours' immersion in water, with a break-down test of 15,000 volts, sustained for an hour, after which the insulation resistance must measure 500 megohms per mile. When the cable is completed, and laid in the ground, a break-down test of 20,000 volts is applied for an hour, and at the expiration of this test the insulation resistance must measure 1000 megohms per mile.

Concentric Cables. The Ferranti mains are concentric cables made in rigid lengths of 20 feet, and a cone sleeve is used to make the connections. The main consists of two copper tubes, one entirely within the other; they are insulated from each other by brown paper steeped in black wax, the outer tube being covered with the same material, and the whole inclosed in an iron tube.

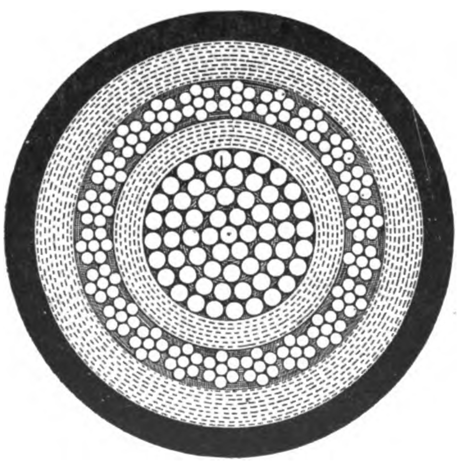


Fig. 240. Concentric Cable.

A common form is that of an inner stranded conductor, and an outer conductor formed by a layer of spirally-wound wires. The jointing of these cables is made by upsetting the outer wires and clamping them between washers, and connecting the washers by a strip of sheet copper; the inner conductors can be soldered, or clamped and then soldered. This kind of cable is shown in Fig. 240. Even if a straight soldered inner and outer joint is made, the joint is so bulky that a coupling-box is clamped on. It is provided

with rubber washers at a, or these chambers are filled with asphalt, to make them water-tight, and the main chamber filled with compound. Such a box and joint are shown in Fig. 241.

There is this difficulty in the use of concentric cables, that it is not possible to ascertain the condition of the insulation between the two conductors without cutting out the dynamo, transformer,

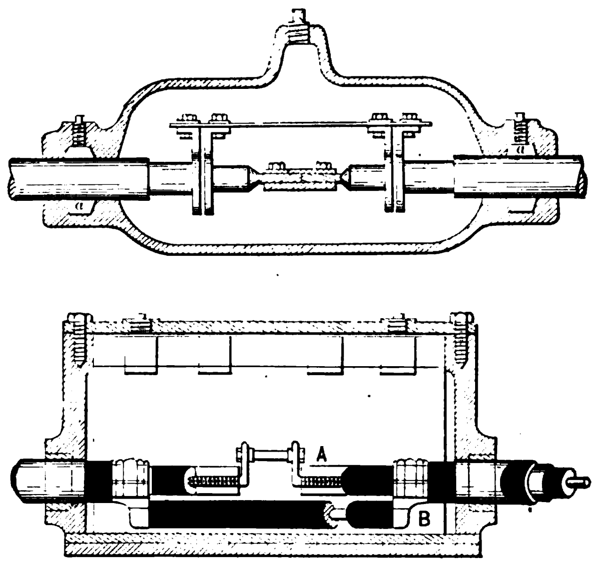


Fig. 241. Concentric Cable Joints.

or other apparatus in the circuit; and therefore the insulation cannot be tested while the circuit is working. This is a serious disadvantage, as with separate cables a continual test may be kept on the circuit, which will often give warning before the fault is sufficiently developed to prevent the circuit being worked. Thus an opportunity is given to localize the fault and repair before any interruption of the lighting takes place.

Joints in Cables. — Joints in solid conductors are generally made by scarfing the ends and soldering; then the joint is tightly wrapped with a serving of copper wire, or a split sleeve put on, the joint being again soldered. The flux must contain no acid.

Stranded cables are made solid by dipping the ends in solder, and treated as above.

In multi-conductor cables the jointing is more difficult on account of the lack of space, and the necessity of getting the insulation between the conductors.

The joint of each conductor is insulated by rubber and compound tape to the desired thickness.

The lead covering is replaced by a piece of pipe previously slipped on the cable, being soldered to the lead sheath, or a wiped joint may be applied. The object in both cases is to get a water-tight joint.

In some cables, after this lead is in place, holes are punched in it, and hot compound poured into the interstices which have been left. The holes are then soldered up.

Manholes. — The various systems in which the conductors are drawn into iron, earthenware, or wooden conduits usually require manholes to be located not more than 200 or 300 feet apart, the cables being pulled from one to the other by means of rope. These manholes ordinarily consist of chambers of brickwork of the general form represented in Fig. 242. They should be provided with two covers, the lower one being screwed down on a rubber gasket so as to be water-tight, and the upper one resting loosely in its place, but being flush with the surface of the street, as indicated.

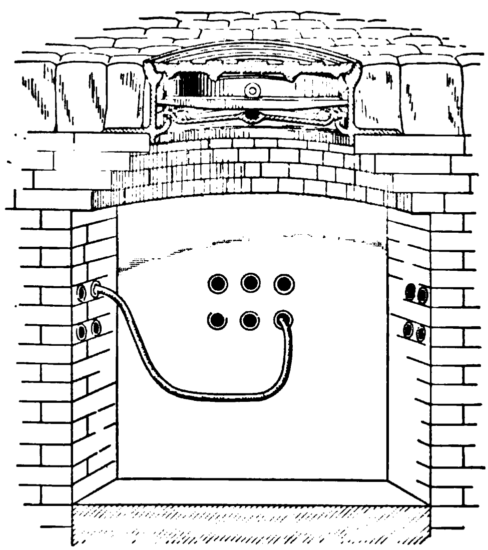


Fig. 242. Cross-section of Manhole.

According to the kind and sizes of the duct, the form of the manhole will change slightly. Fig. 243 shows a manhole used in connection with vitrified multiduct conduit. Fig. 244 will give a good idea of the interior of a manhole looking down into it from the street.

In dry or porous soils the bottom of the manhole is some times

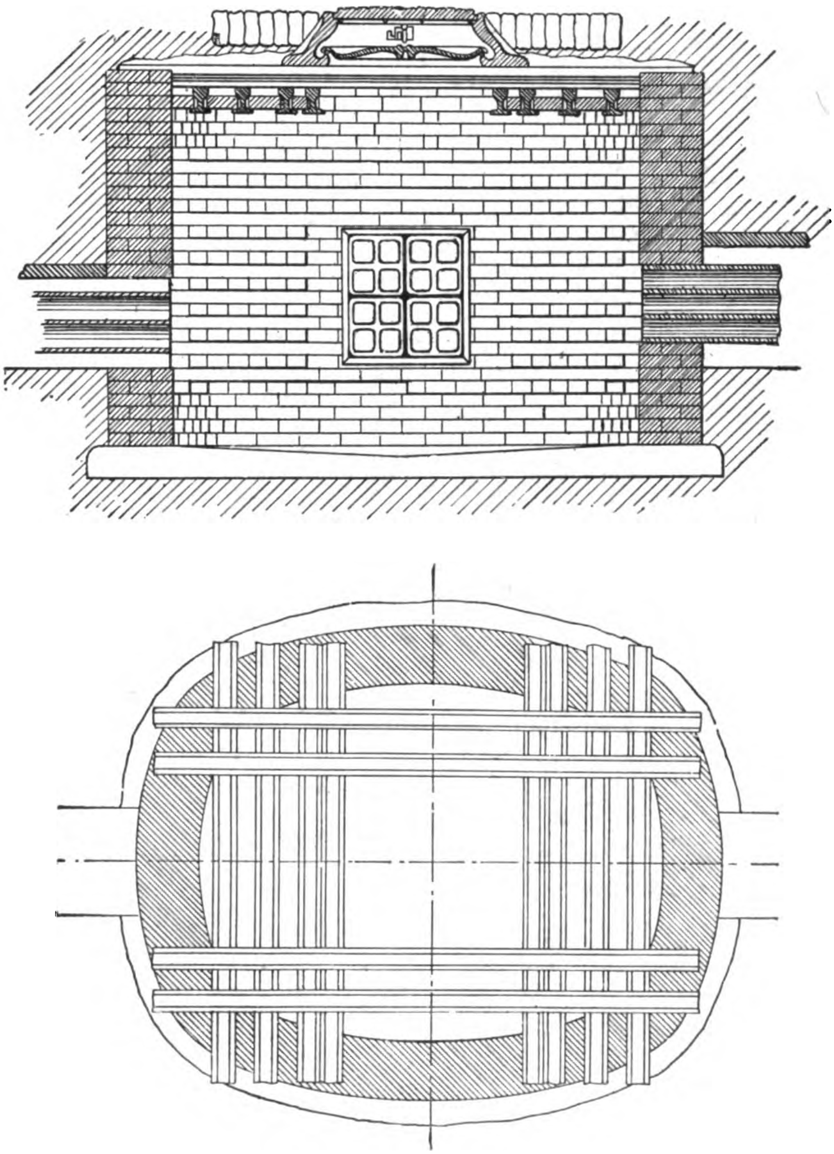


Fig. 243. Brick and Iron Manhole.

left out so as to drain it; when this is not feasible a sewer connection is make to accomplish the same result.

The typical manhole adopted for the New York subways is shown in Fig. 245, being drained by a pipe P leading to the sewer.

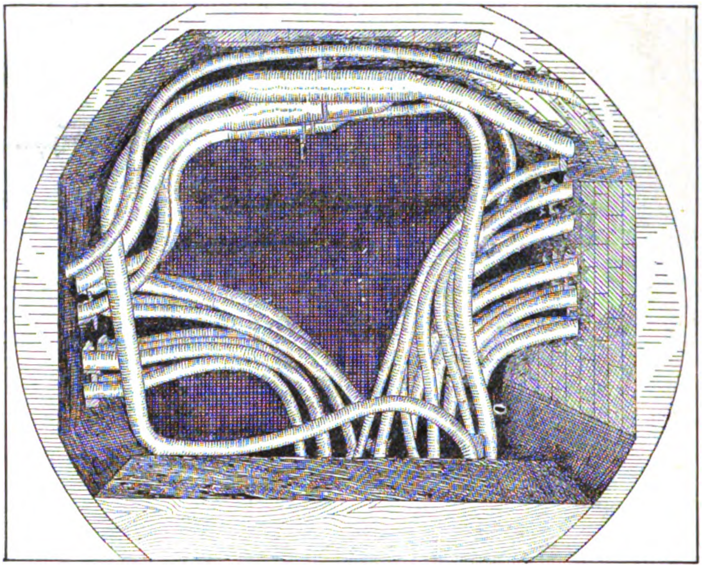


Fig. 244. View into a Manhole.

Fig. 246 is a view of the iron-pipe conduit used extensively in the city, showing a service box in place, being practically a small manhole with side connections for the buildings. Fig. 247 shows such a box. When the number of the ducts is not large, as in local distribution, the manholes and service boxes become mere hand-holes.

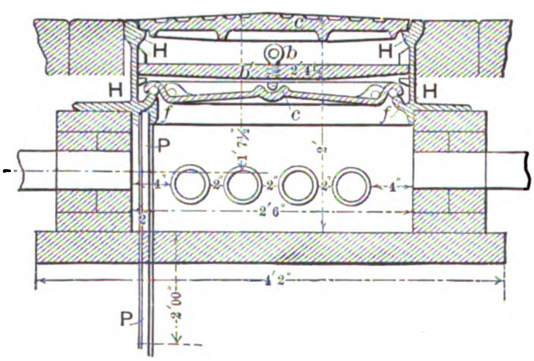


Fig. 245. New York Subway Manhole.

Drawing in the Conductors. — Since a duct is entirely empty when built, and is usually from 200 to 300 feet long between manholes, it is necessary to employ some special means of getting

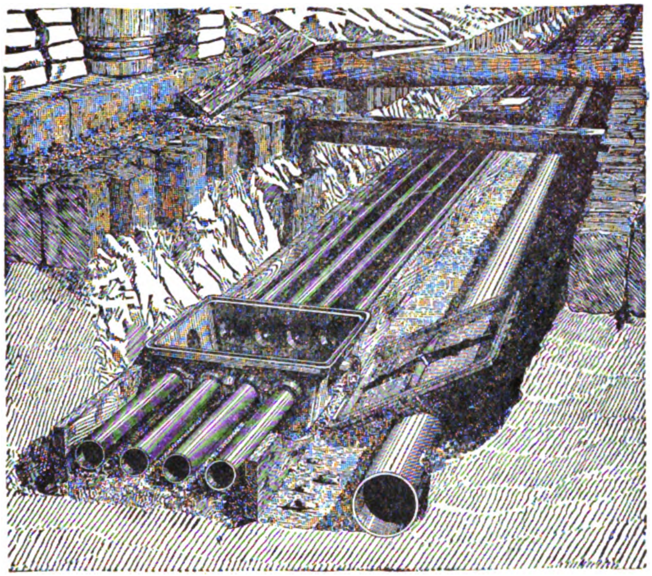


Fig. 246. Iron Pipe Conduit.

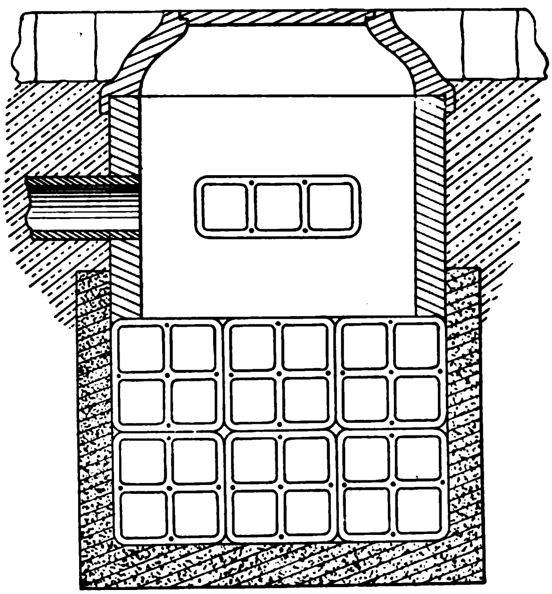


Fig. 247. Service Box for Terra Cotta Conduit.

a rope through it in order to draw in the cable. One plan is simply to push through a steel tape or wire, which is provided with a rounded metal head to prevent the end from catching in the joints between the pipes. By means of this tape or wire, a small and then a large rope may be pulled through the duct. Another method is the so-called "rodding" of the ducts, a 20-minute operation, consisting in inserting one after another into a duct, short rods of wood or steel, about 3 or 4 feet long and $\frac{3}{4}$ inch in diameter, which are connected together by screw or bayonet joints, as indicated in Fig. 248. When a sufficient number have been joined to reach from one manhole to the next, a small rope is attached to a ring in the last one, and the rods are then pulled through from the other end, being unjointed as they come out. A larger rope may then be drawn through, after which a steel scraper and a brush should be pulled through the duct in order to clean it, and remove any stones, tools, etc., that are often found in it and would be very likely to injure the cable. These are illustrated in Fig. 249.

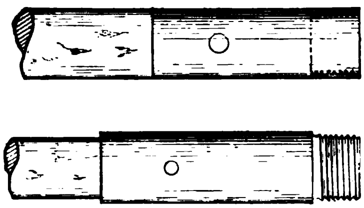


Fig. 248. Rods for "Rodding Conduits."

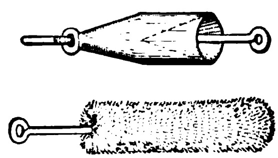


Fig. 249. Scraper and Brush for Conduit.

After the duct has been cleaned properly, the end of the cable is attached to a heavy rope which has been drawn through the duct by attaching it to the cleaning implements. In attaching the cable to the rope, care should be exercised to avoid bringing undue strain on the copper conductor or its insulation during the operation of drawing in the cable. This may be done by putting a conical metallic head on the end of the cable, or by winding several iron wires spirally around the last foot or two of the cable, and forming these into a loop to which the rope is attached. For hard pulls and curved pipes the end of the cable is served, after removing about 18 inches of the lead and the insulation. The strands of the cable are then fanned out, and divided into four groups, and passed through a shackle as shown in Fig. 250; they are bent back on themselves, and bound tightly with spun yarn or wire. If the pull is to be extra hard, an iron wire may be also put through the

shackle, and driven through the lead sheath. This gives an excellent hold on the cable, distributing the strain over all the conductors, as well as to the lead covering.

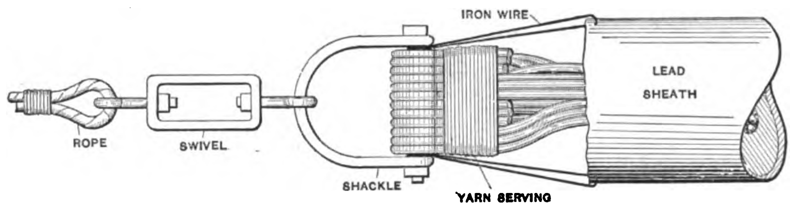


Fig. 250. Attachment for Cable to Rope.

Having attached the cable through a swivel to a strong rope, it is drawn into the duct by means of an apparatus shown in Fig. 251. The cable unwinds from the drum D, as it is drawn by the winch W.

It is evident that the cable should be somewhat smaller than

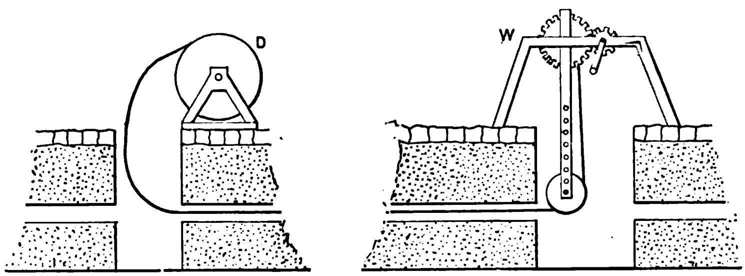


Fig. 251. Winch for "Drawing In" Cable.

the duct through which it is drawn, but the margin need not be great. For example, cables $2\frac{5}{8}$ inch in diameter can be drawn through the standard 3-inch ducts. When several cables are to be put in the same duct it is much better to draw them all in at the same time; but it is possible to draw one into a duct already containing others, provided there is space enough. It is also possible to withdraw one or several cables from a duct without serious injury to them, in case repair or change becomes necessary.

Methods of Distribution from underground conduits constitute one of the most serious problems in connection with them. The main or trunk lines may be provided for by the various forms of conduit that have been described, but these do not readily allow branch connections to be made at frequent intervals to supply individual buildings. It is decidedly objectionable to complicate and

weaken the construction of the main conduits by having side connections, so that the best plan is to keep those intact, and provide a subsidiary duct or conduit into which the conductors required for local distribution are run at one of the manholes. Such an arrangement is shown in Fig. 252.

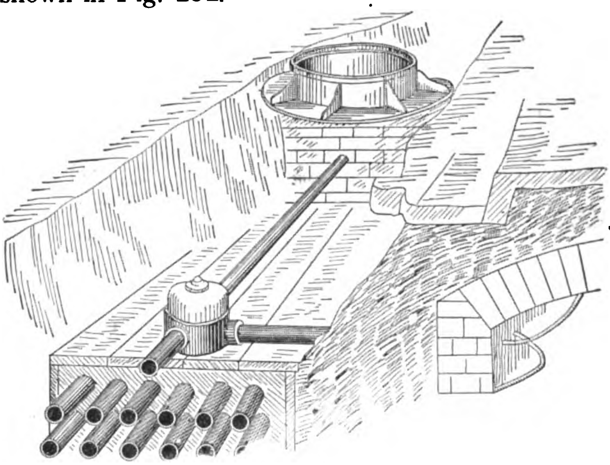


Fig. 252. Hand-hole Distribution.

In Figs. 253 and 254 are shown iron subsidiary service boxes for use in connection with terra-cotta conduits.

The Edison system of distribution is well shown in Fig. 255 which illustrates also a distributing box and service box.

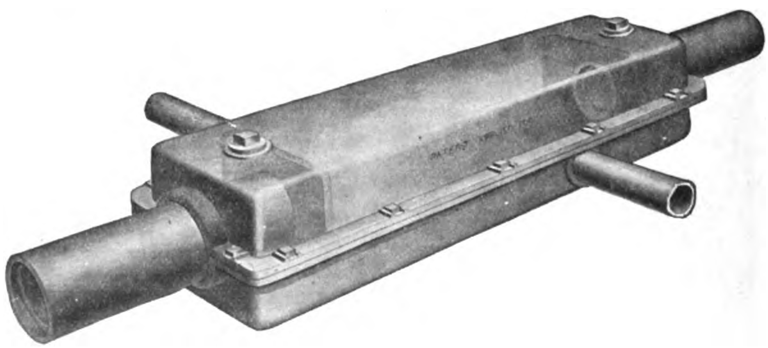


Fig. 253. Iron Service Box for Pipe Conduit.

The house vault, back yard, lamp-post, housetop, hand-hole methods of distribution are easily seen to refer to the way by which the service cable passes from the subway to the building. Street arc lamps may be supplied as indicated in Fig. 256.

In Baltimore there is a complete system of distribution, shown in Fig. 257, and consisting of two separate parts.

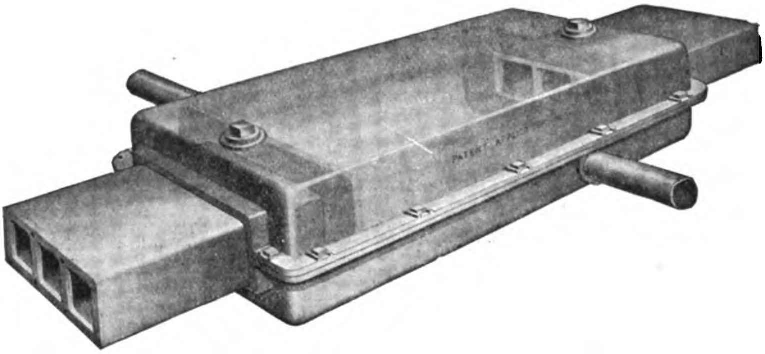


Fig. 254. Iron Service Box for Terra-Cotta Conduit.

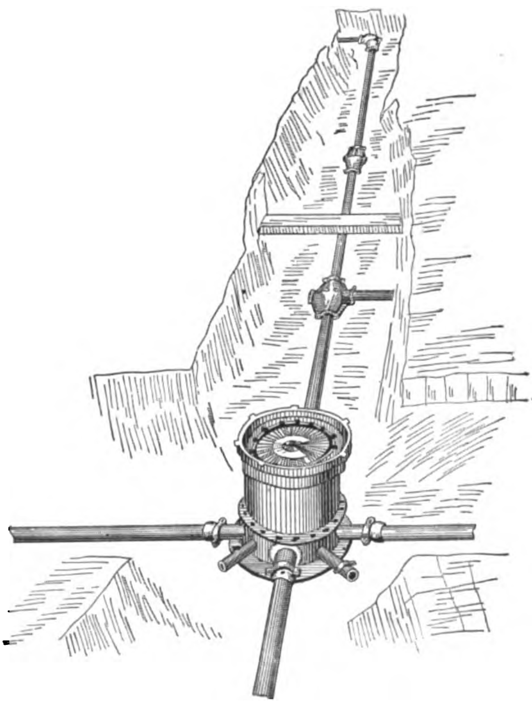


Fig. 255. Edison System of Distribution.

For high-tension distribution there is a wrought-iron pipe duct with service boxes to transformer pits, consumers, etc., being entirely a subway, and entering buildings through cellars.

For low-tension mains there is a conduit system of wrought-iron tubes, cement-lined tubes, or terra-cotta duct, leading to pole terminals situated on each block, and thence overhead to consumers.

VENTILATION OF UNDERGROUND CONDUIT SYSTEMS.

Considerable difficulty has been experienced in satisfactorily ventilating subways carrying electric light and power conductors. When these systems were first introduced they were made as nearly as possible air-tight and the covers of manholes hermetically

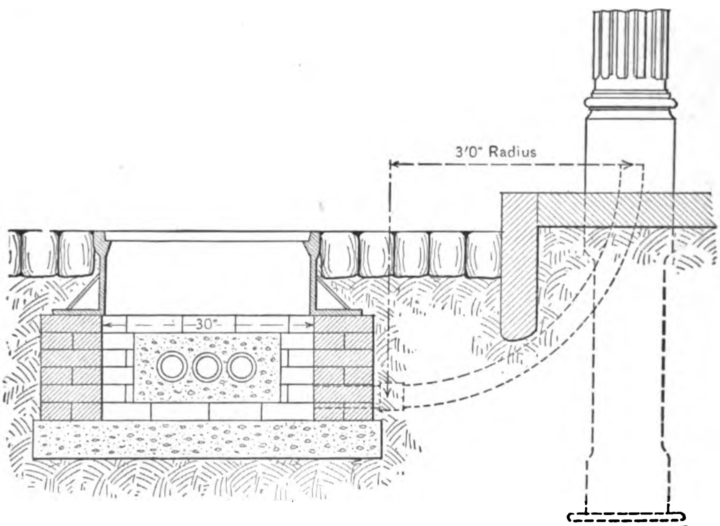


Fig. 256. Lamp-post Connection.

sealed. The porosity of the material forming the walls, etc., defeated this end, and allowed gas to enter the different parts of the system where it mingled with air. The blowing of a fuse or a spark due to some other cause would often ignite this mixture of air and gas, and destructive explosions sometimes resulted.

To avoid this danger pumping equipments were arranged to remove the air from the subways. This at first seemed effective, as it tended to keep the air in the subway in motion, but it also induced gas to enter, due to the partial vacuum caused.

After abandoning this scheme a new arrangement was introduced known as the blower system. This was based on the idea that if

an air pressure was maintained in the subway it would prevent outside gas from entering. The fallacy of this hypothesis was soon evident, owing to the law that if two gases are separated by a porous diaphragm, even though greater pressure is maintained on one side

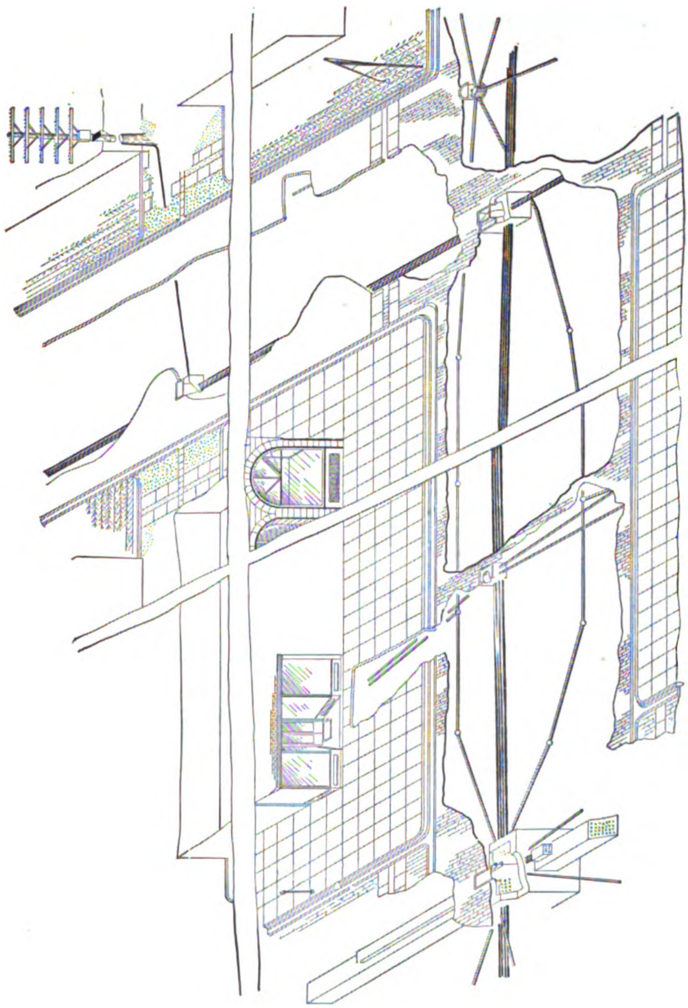


Fig. 257. A Complete System of Distribution.

than the other, the gases will still mix. The brick walls in the subway acted in this case as the diaphragm; and explosions still occurred after the introduction of this ventilating system, although of less frequency and violence. Tests showed, moreover, that the

blower system produces practically no pressure except within a radius of a few blocks from the station.

It was then decided to employ gangs of men who would visit various manholes, remove the covers, and let the subway at these points become ventilated. Owing to the excessive cost of these methods they were finally abandoned. The ventilation of manhole covers was then considered. The chief objection to ventilating covers was that they would allow the subway to fill up with water and dirt, and thus cause trouble. This proved, however, not to be the case in practice; for late experiments show that the dirt and water accumulated in very small amounts, and that only a small force of men was needed to remove such accumulations. The amount of gas which collects in the conduits proves relatively much less than with the blower system, and the total saving is very considerable.

The escape of gas from the gas mains still constitutes a source of much annoyance and danger, and even at the present time the precautions above mentioned have not proved sufficient to entirely eliminate the dangers of explosions.

For further information regarding Underground Electrical Conductors reference may be made to the following works:

Electric Transmission of Energy by A. V. Abbott, Second Edition, N.Y., 1899.

Electric Distribution by Kilgour, Swan and Biggs, London, 1893.

Electric Light Cables by S. A. Russell, London and N. Y., 1892.

Localisation of Faults in Electric Light Mains by F. C. Raphael, London and N. Y., 1898.

Ligues et Transmissions Electriques par Weiller et Vivarez, Paris, 1892.

CHAPTER XIV.

THE ELECTRIC ARC.

Definition. — The electric arc is the phenomenon of light and heat occurring when an electric current persists in maintaining itself across an opening made in its circuit. When of short duration and of disruptive character it is known as a spark; the term *arc* being used to designate a continued discharge across a bridge of conducting vapor.

History. — The spark was first observed by Volta in 1800, in which year, too, Sir Humphry Davy discovered the particularly bright spark between charcoal points separated in air or under liquids, and exhibited it before the Royal Institution with the aid of a battery of 150 elements. It was not until 1808 that Davy, with a battery of 2000 elements, was able to exhibit the first true arc, an extended flame nearly four inches long, before the Royal Institution. This discharge was maintained between horizontal charcoal points, and owing to the current of heated air which is created, assumed a bow or arch shape; hence its name of "arc."

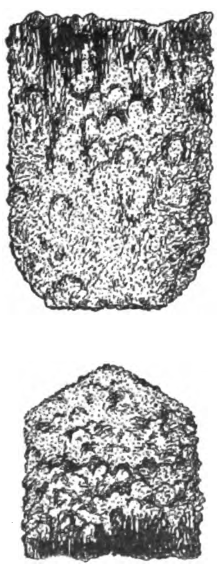
The intense brilliancy and whiteness of this light resulted in wide-spread efforts to utilize it practically; and numerous improvements followed, chief of which was Foucault's introduction in 1843 of gas-coke carbons to replace those of charcoal hitherto used. Another early step in advance was Grove's use of the salts of sodium and potassium to steady and increase the length of the arc. The application of the arc to practical purposes was often attempted, but the cost of electrical energy generated by a primary battery is so high that no commercial success was accomplished until the dynamo had been developed.*

General Features of Arc. — An arc may be maintained by either direct or alternating current. Under ordinary circumstances the

* Vol. I., pp. 8–17.

two electrodes must be brought together before being separated to establish an arc, otherwise several thousand volts pressure would be required to strike across the air-gap in the first place. As soon as the separation of the terminals commences, the spark, which tends to form at any break in a circuit, vaporizes a portion of the material of the electrodes, thus establishing a bridge of conducting vapor through which the current flow is maintained. The concentration of energy in a small space produces an intense heat, which vaporizes the electrodes rapidly, so that a highly refractory terminal must be employed to avoid its rapid consumption. Moreover, the intensity of light given out by the arc depends on the temperature to which the electrodes can be heated without being vaporized, therefore a highly refractory substance like carbon best fulfills the requirements.

Appearance. When an arc is sprung between two carbon rods placed vertically one over the other, and kept about one-eighth of an inch apart, a constant current of about 5 to 15 amperes will produce a stationary condition after a few minutes burning. If observed through smoked glass, or, better still, if the image of the arc and carbons be projected upon a white screen by a lens, it will be seen that both carbons tend to become bluntly pointed, because oxidized away by the heat; but the positive carbon, which is usually the upper on account of its emitting more light, will have a hollow, or "crater," at the tip. This may be .04 inch deep and 2. inch across under average conditions. This is the hottest and most luminous portion of the carbons, attaining a temperature of approximately 3500° C. as Violle proved, breaking it off and dropping it into a water calorimeter. The intense heat thus generated can be realized when the melting point of platinum is considered, which is 1,775° C. The negative electrode exhibits no tendency to become hollowed, and remains pointed. In fact, the carbon particles burned from the tip of the positive carbon tend to deposit in the shape of a point or nib on the negative carbon, which is much cooler and less luminous than the positive.



258. Appearance of Arc Light Carbons.

Both carbons appear luminous some distance away from the tips, this being especially noticeable on the positive. If the carbons contain impurities, these may generally be seen in beads near the tips, to which they often work their way to be instantly volatilized. Between the carbon points is the arc stream proper, which assumes a bow shape even when the carbons are vertical, owing to the magnetic action of the earth's lines of force on the current. The inner portion of the arc stream consists of a violet hub, probably of incandescent carbon vapor, surrounded by a thin non-luminous portion where the carbon combines with the oxygen of the atmosphere in dark flame to form carbon monoxide (CO). This is enveloped in turn by a layer of luminous flame in which the carbon monoxide burns to carbon dioxide (CO_2). The magnified image of an arc on a screen will show occasional carbon particles flying from the positive (which on the screen seems to be the lower carbon) to the negative, while other particles are thrown off into space by the action of the heated air.

Noise. Under favorable conditions the arc is perfectly quiet, but emits a hissing sound like frying if the current exceeds the proper value for the length of arc employed.

Odor. A distinct odor is noticeable close to the arc, especially in damp weather, probably due to the presence in small quantities of hydrocyanic acid gas. Besides this, carbon monoxide and dioxide as well as nitric oxide are usually present; but none of these gases is given off in sufficient quantity to be injurious where the voltage of the arc does not rise above 55 in air.

After some minutes burning, it will be observed that both carbons waste away, the positive as a rule being consumed in the open direct current arc about twice as fast as the negative, the ratio depending on various conditions. For this reason the carbons must be fed together by hand or by some automatic device, otherwise the length of the gap would increase until its resistance exceeded the power of the generating apparatus to maintain a current through it.

Physics of the Arc. — Under commercial conditions direct current open arcs usually consume about 10 amperes at 45 volts or 450 watts. Thus nearly one-half k. w. of energy is concentrated in heating up the small extent of the crater and arc, resulting in the production of the very high temperature of 3500° C.

taken to be the boiling-point of carbon. That carbon is volatilized in the arc is undoubtedly a fact. The surface of the crater has the appearance of boiling; the hissing noise occurring with excessive current density is similar to that produced by violent boiling of water, and may result from the same cause, though carbon, like arsenic, vaporizes directly from the solid state. Carbon consumption goes on in a vacuum, although at a slower rate than in air, and the vapor thus formed condenses on the sides of the inclosing chamber. These facts all go to show that carbon is actually evaporated. Such being the case, the temperature of the surface of the carbon would naturally remain stationary at this boiling-point, like the temperature of boiling water at atmospheric pressure, whatever the heat applied. The temperature of the negative carbon, except at its extreme point, is considerably lower than that of the positive. The difference is due to the fact that the larger part of the energy is transformed into heat at or near the surface of the positive carbon. This is evident from the relative appearance of the two electrodes and is demonstrated experimentally by measuring the distribution of potential between the carbons. The most reliable observations show that about 40 volts drop occurs between the positive and the arc stream, with only $2\frac{1}{2}$ volts in the stream and $2\frac{1}{2}$ volts between the stream and the negative carbon.

The temperature of the space between the carbons may be much higher than that of the surface in the same way that steam can be superheated above the point at which it is evaporated, there being, in fact, no limit to the possible rise in temperature. Since the current is conducted by the highly heated vapor present, it is to be expected that such a conductor will be heated by the passage of a current the same as a solid or a liquid.

Theory. — It is evident that the amount of carbon vaporized at the positive crater forming the arc stream will vary with the current, therefore the resistance of the arc, which varies inversely with its cross-section, varies inversely with the current. In this respect the arc is totally unlike solid or liquid conductors, whose resistance is independent of the current, other conditions remaining the same. Hence Ohm's law in its general form is inapplicable to the arc stream.

The fact that the phenomena at the arc are more or less rever-

sible, since the vaporized carbon can again be converted into the solid state by condensation, points to the existence of a *counter-electro-motive force*, and since the temperature of the vaporization is constant, or nearly so, the counter electro-motive force should also be constant, which appears to be the case. Physicists have long sought to isolate and determine this experimentally, and it would seem that such a definite physical problem could easily be solved; but there are peculiar difficulties, which up to the present time have rendered all methods and results questionable. There are great difficulties connected with retaining the arc, whose carbons are constantly changing, at a constant condition, and a long time is required to permit the arc to assume a stationary state. Further, the depth of the crater, and consequently the true length of the arc, is very hard to measure at any given moment. Again, the resistance varies with the length of the arc and in some inverse ratio with the current. Add to this the difficulty of securing pure carbons whose density, electrical conductivity, and heat conductivity are uniform throughout, and the utter impossibility of retaining the counter-electro-motive force after the current which induces it has ceased to flow, and the difficulties become more apparent. By indirect methods an approximate value of 35 to 39½ volts has been arrived at for arcs of 10 amperes and 45 volts and pure carbons. The indications point to a counter-electro-motive force at the arc, variable with the current and other conditions. In fact, it is very likely that it consists of a combination of two or perhaps more separate electro-motive forces; one due to the volatilization of the carbon, another due to the thermo-electric effect at the positive carbon, and perhaps still another thermo-electric potential at the negative carbon.

Voltage dependent on Boiling Point. — From what has already been said, it seems probable that whatever tends to raise the boiling point of carbon will likewise raise the voltage required to maintain an arc, a conclusion confirmed by experiment. Increase of atmospheric pressure, other conditions being constant, increases the arc voltage. Similarly we should be able to reduce the voltage by lowering the vaporizing point of the crater, an effect which is found to result when more volatile substances, such as the salts of the earth metals, are introduced, usually in the form of a core.

Resistance. — The resistance of an arc, like that of any other

conductor, increases with its actual length, and diminishes with its cross-section. The length of an arc usually given is the apparent length; that is, the distance from the *edge* of the crater to the tip of the negative. The true length is, of course, the distance from the *bottom* of the crater to the tip of the negative. A case may easily be imagined where, owing to the varying depth of the crater, the apparent length might be diminished yet the actual length increased. Failure to distinguish between these two is apt to result in misleading conclusions. The cross-section of the arc varies at different points between the carbons, since it has a tendency to spread out from electric repulsion, which causes its section to be greatest about midway between the carbon points. The arc stream tends to spread out farther as the carbons are drawn apart. The area of the crater, which is, of course, one end of the arc stream, has been found by Ayrton to vary approximately according to this law: $D = .128 \times .15\ A$; where D is the diameter in inches, and A is the current expressed in amperes.

The resistance of the 10-ampere arc is $\frac{1}{10}$ to $\frac{1}{2}$ an ohm for arc lengths from about $\frac{1}{16}$ to an $\frac{1}{8}$ of an inch in length. Houston and Kennelly give 5 ohms per inch as a rough general value.

Carbons. — There are two classes of carbons used in arc lighting, solid and cored. They may be of any diameter. For the sizes usually employed the average resistance is 0.15 ohms per foot.

Solid carbons vary according to their purity, molecular structure, and hardness. *Cored* carbons are solid except for a hole running axially through the carbon, filled with some material more soft and volatile than the remaining carbon — being usually a mixture of carbon and some metallic salt.

Object of Core. The object of this core is first to decrease the voltage for a given length of arc, as already explained, or to increase the length for a given voltage. This has the initial effect of reducing any irregularity in carbons or the feeding mechanism to a less percentage of the whole length. Further, the core, by affording a plentiful supply of vapor, tends to maintain a stable condition of the arc. It also keeps the arc located in one spot, and prevents the tendency to travel irregularly around the carbon due to the arc seeking the path of least resistance. When this traveling occurs it gives rise to an objectionable flicker, owing to the shadow

of the carbons being shifted in different directions, and to the variations of energy which occur faster than the mechanism can follow. A core may be employed also to modify the color of the light, as for instance to produce a yellowish tinge due to the well-known sodium flame. With these facts in mind, we can explain many phenomena found in arcs as used in practice.

Carbon Consumption. — With similar carbons placed vertically one over the other, the relative consumption will depend on the amount carried off by: —

Volatilization and electrolytic action.

Oxidation of the air.

Mechanical disintegration by air currents.

When carbons of different diameters are used, their life increases roughly in proportion to their sectional area, barring the oxidation of the air. The latter is frequently reduced, and the conductivity of the carbon increased, by plating about nine-tenths of their cylindrical surface with a thin layer of copper, leaving the tip uncoated; but the primary object of the plating is to reduce the contact resistance of the carbon.

Volts and Amperes. — The volts and amperes required depend greatly upon circumstances; but for the open arcs usually employed, the amperes range from six to ten, and the volts from forty-two to fifty-two: a common value would be 47 volts and 9.6 amperes. In search-light projectors much heavier currents are frequently employed, from 50 to 150 or 200 amperes, with voltages from 48 to 53. With these heavy currents, the carbons become hotter, and are oxidized farther back from the ends, resulting in longer points.

Physical Phenomena. — The positive carbon wastes away electrolytically inside of the crater, and by the action of the air outside of the crater, causing it to waste away about twice as rapidly as the negative in the open arc. The negative carbon is consumed by oxidation of the air alone, according as its temperature is increased by the carbon particles deposited on it, and by the heat reverberated from the positive crater. The closer the positive approaches the negative, the greater will be its roasting effect on the latter. With very short arcs, the deposit of graphitic carbon upon the negative accumulates faster than it wastes away, so that it forms a nib or second point on the top of the negative which finally

crumbles away. This action may or may not be accompanied by a hissing noise.

Carbon turns to Graphite. Carbon that has been exposed to the heat of the arc turns to graphite. The hard pencils of solid carbon used for high-tension lamps will not mark paper before being used. After having been burned a few minutes the tip of the negative will write black like a pencil, and even the point of the positive will show some graphite.

Electrical Relations. — With both solid and cored carbons a point may be reached when the voltage will be constant if the arc length and current are kept the same. This is called the stationary state. In Fig. 259 the relation of the voltage to

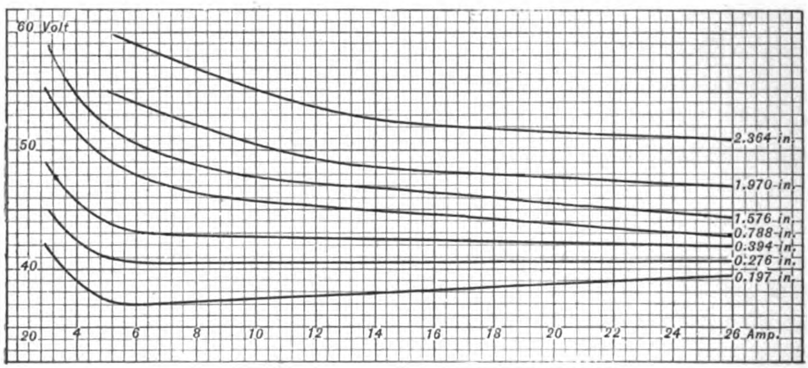


Fig. 259. Voltage and Current with Cored Carbons.

current is plotted for several apparent arc lengths with both carbons cored. It will be noted that with short arcs, less than $\frac{1}{25}$ inch long, the voltage rises as the current increases, due to the increased CR drop. With arcs longer than $\frac{1}{25}$ inch, on the other hand, the voltage falls with increasing current, due to the expansion of the long arc, whose larger cross-section more than compensates for the drop caused by increasing current. This, at one time, gave rise to a theory that the arc had a negative resistance, an entirely unwarranted conclusion. For arcs of $\frac{1}{25}$ inch, the spreading action of the stream exactly counterbalances the increase current; so that for this arc length the voltage remains constant within wide fluctuations of current. In arcs shorter than $\frac{1}{25}$ inch the stream has no room to spread laterally. Another reason for

the lower voltage with increased current shown by the curves of longer arcs is that the current increases while the cooling surface does not, so that less energy, and consequently less voltage, are required to maintain the arc at the same temperature.

Effect of Cored Carbons. The same relations are shown in Figs. 260 and 261, except that the results are for a cored and

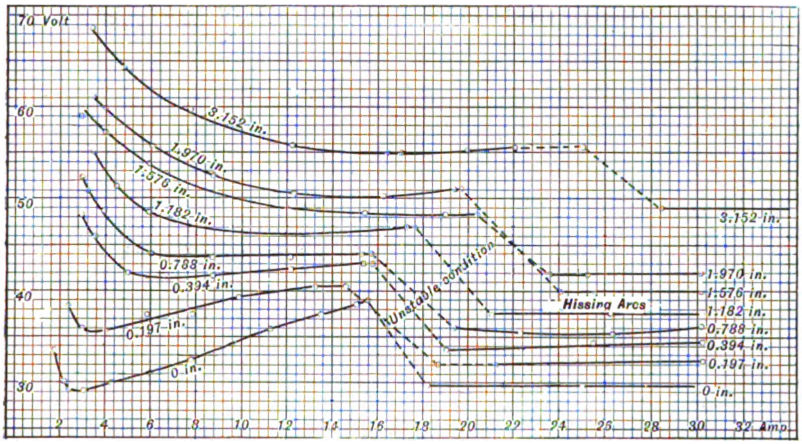


Fig. 260. Voltage and Current with Solid and Cored Carbons.

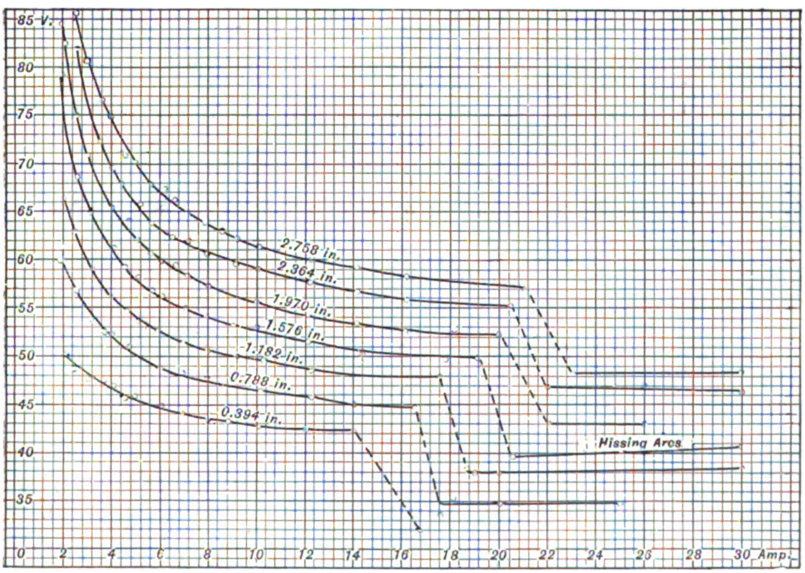


Fig. 261. Voltage and Current with Solid Carbons.

solid, and for two solid carbons respectively. The former show conditions approaching those found when using both carbons cored. But beyond a certain current strength all the arcs pass through a condition of unstable equilibrium, and no length can be found where the voltage will remain constant for all currents, plainly demonstrating one of the advantages of using cored carbons. When both carbons are solid no length of arc gives even approximately constant voltage with varying current and a quiet arc. The constant voltage beyond the unstable condition is for *hissing arcs.* With cored carbons the voltage is from 3 to 6 volts less than with solid carbons, owing to the greater volatility of the electrode.

Resistance of the Arc. — If the current is kept *constant* the resistance of any arc *increases* with its *length.* With solid carbons the ratio is a linear one as shown by Fig. 262, and nearly so for cored carbons as given in Fig. 263.

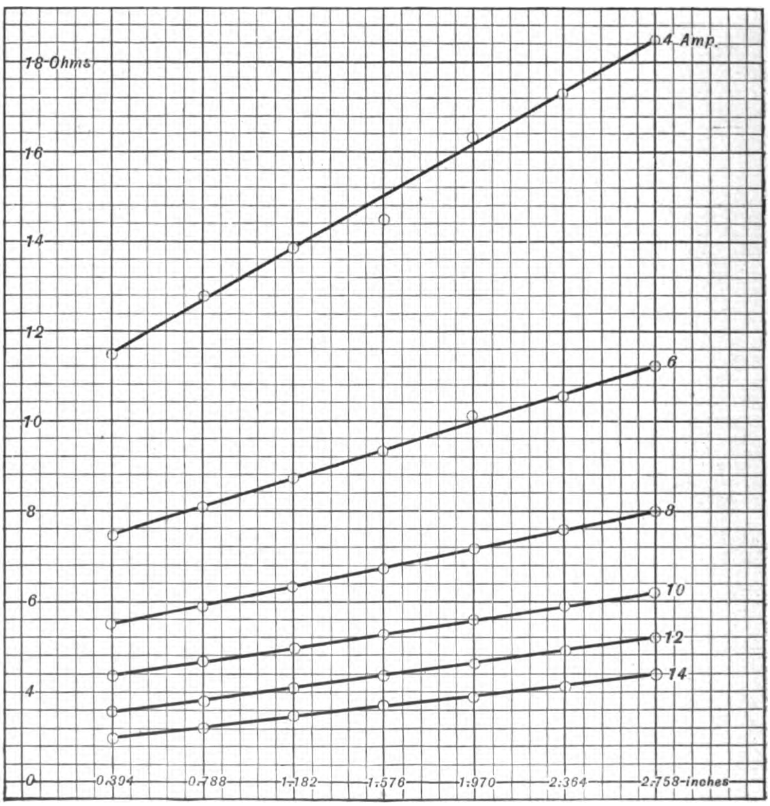


Fig. 262. Resistance for Different Arc Lengths with Solid Carbons.

As explained before, if the current is variable, the resistance of the arc stream proper varies inversely with the current. Therefore, the apparent resistance of the arc, which is the quotient of the volts and amperes, may be expressed by the formula,

$$R = x + al,$$

where x is some quantity varying inversely with the current and a is a constant. Multiplying both sides by the current I we have

$$IR = xI + aIl.$$

$IR = E$ and xI is composed of a term varying inversely with the current and one directly proportional to it, so that we may sub-

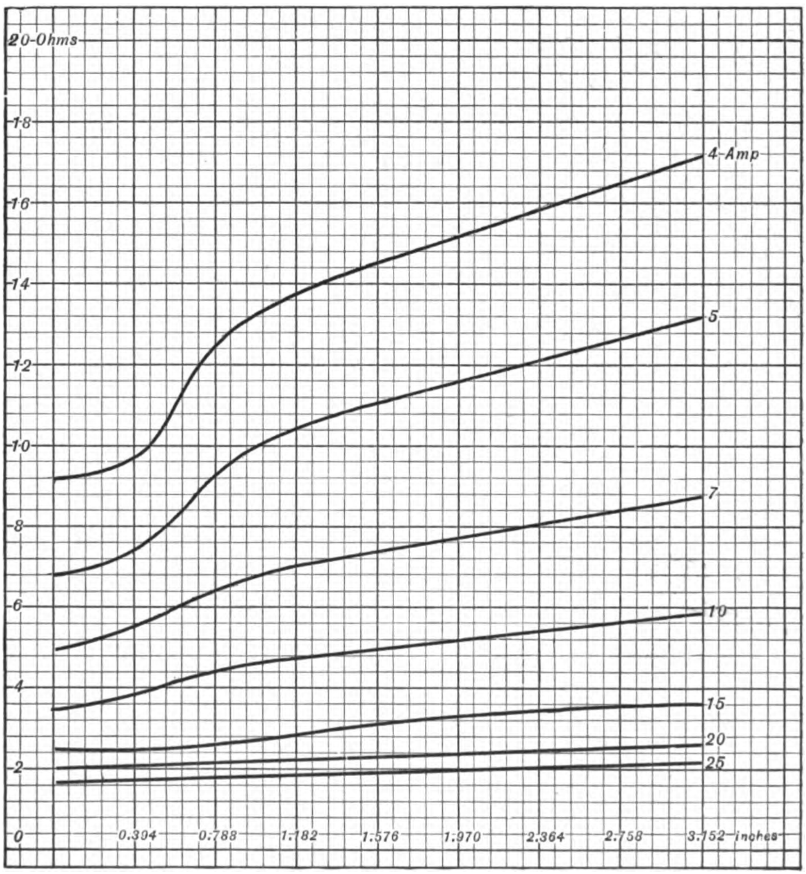


Fig. 263. Resistance for Different Arc Lengths with Cored Carbons.

stitute a constant m for it. We may also substitute a value n for the product al, so that the voltage E at the arc is

$$E = m + nl.$$

The most probable values of these quantities for good solid carbons seem to be those obtained by Duncan and Rowland for good pure carbons, namely, $m = 40.6$ and $n = 40$, where l is the length of the arc expressed in inches.

Watts at Arc. — If the *current* is kept constant the watts increase in a linear ratio with increase of arc length as shown by Fig. 264. If the *arc length* is constant and the current increases, the watts will vary in a similar manner, as shown by Fig. 265.

Hissing Arc. — When an arc is shortened, or its current increased until it hisses, the voltage drops 10 to 20 volts, and stays constant even when the current varies greatly (Figs. 260 and 261), for which no satisfactory explanation has been afforded.

Photometry of the Arc. — The chief source of light in the arc is the intensely heated crater, which gives about 85 per cent of the total light. The arc proper, or flame between the electrodes, is almost non-luminous, giving only about 5 per cent, while the tip of the negative carbon gives about 10 per cent. Owing to the form and arrangement of the carbons, as shown in Fig. 258, most of the light is thrown down when the positive carbon is above, as it usually is. The exact distribution varies with the current, carbons, and other conditions; but the general distribution of light from a continuous current arc is shown in Fig. 266. The lengths of lines drawn from the arc to points on this curve represent the relative candle-power at different angles. It is evident from this diagram that it is possible to obtain various values for the candle-power of the arc according to how the measurement is made. As a matter of fact, candle-power is actually measured in four different ways:

Candle-Powers. — 1. The mean horizontal candle-power, usually the smallest of the four, being the average in all directions in a horizontal plane.

2. The mean hemispherical candle-power, usually greater than the last, which is the average obtained by making measurements in all directions and angles below the horizontal, showing the average value of the illumination thrown downwards.

3. The mean spherical candle-power, determined in a similar

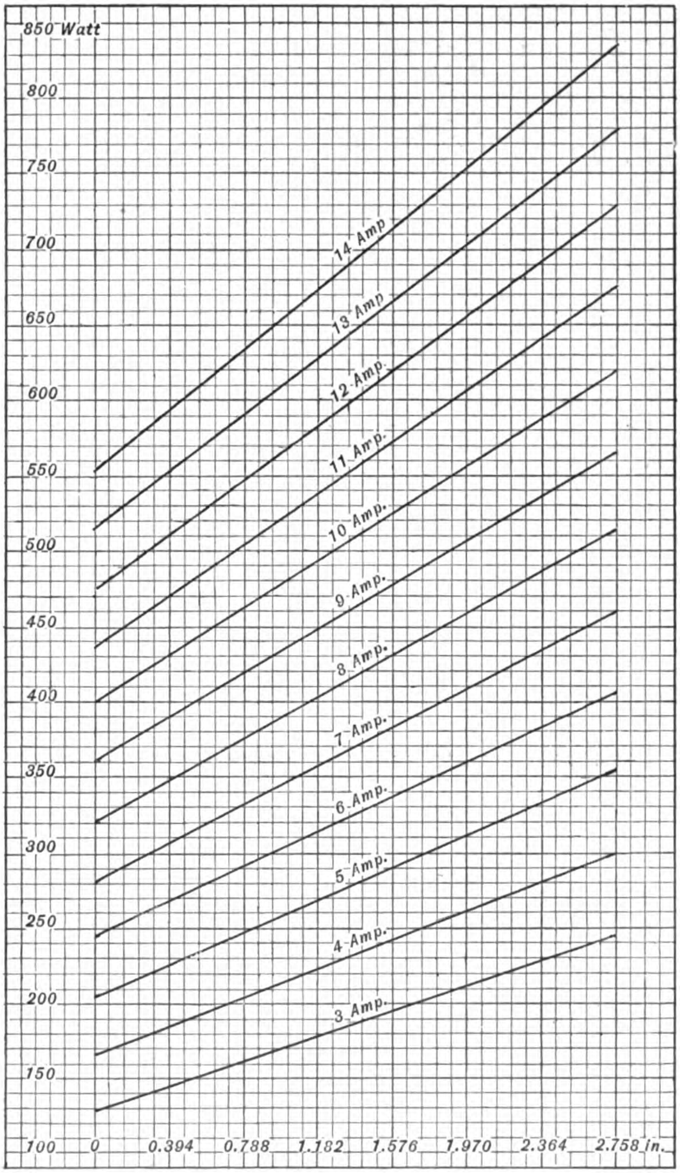


Fig. 264. Power consumed for Different Arc Lengths.

way, but the mean of measurements at all angles above and below the horizontal. This gives the true average candle-power of the arc in all directions.

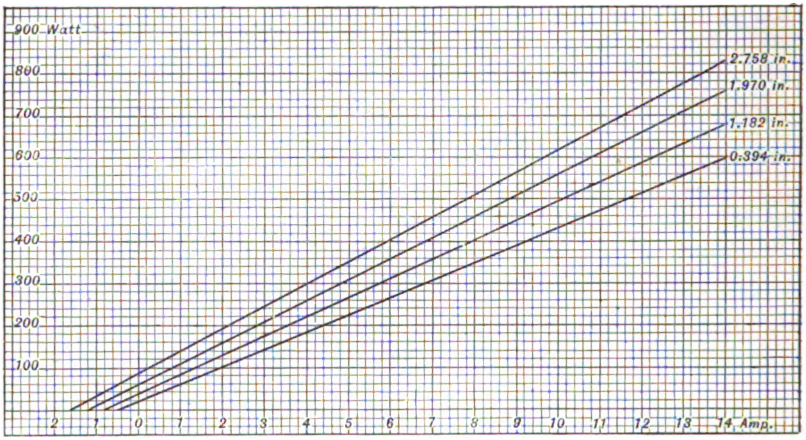


Fig. 265. Power consumed for Different Current Strengths.

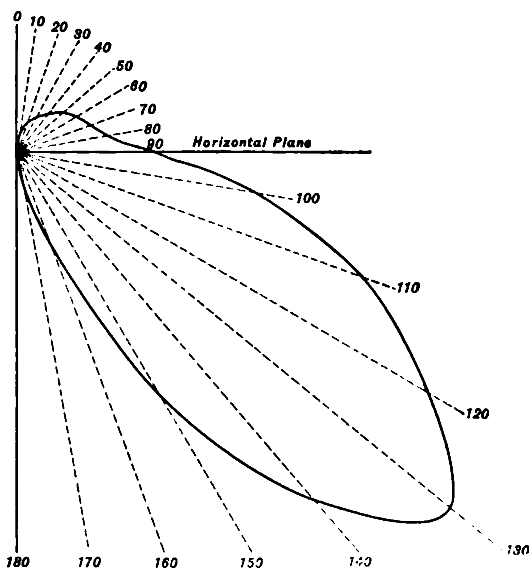


Fig. 266. Light Distribution, Direct Current Open Arc.

4. The maximum candle-power found by making observations in all directions to ascertain the greatest candle-power. This is usually found at an angle of 40 degrees below the horizontal.

The term "*nominal candle-power*" is often employed in commercial work, meaning a value arbitrarily agreed upon to correspond to a certain consumption of energy at the arc. Thus an arc consuming 450 watts is assumed to have 2,000 nominal candle-power, and one of 300 watts to have 1,200 candle-power; although these figures greatly exceed the true spherical candle-power, they may come somewhere near the maximum under favorable conditions. As a matter of fact, the relation between watts and candle-power is quite variable, as shown later.

Of the various candle-powers the mean spherical candle-power is the most absolute and important, but unfortunately is the most difficult to determine. The mean hemispherical candle-power may be properly considered where illumination is required in one direction only, as in street-lighting, where the light is thrown outward and downward. The mean horizontal candle-power is of no special importance, the light given off in a horizontal plane being of no more value than that emitted in any other direction; but it is quite easily measured, and often approximates closely to the mean spherical. This is, however, not always the case, and cannot be generally relied upon. The formula due to Gerard is sometimes employed to find the mean hemispherical candle-power by simply measuring the horizontal and maximum candle-power, the expression being:

Mean hemispherical candle-power = $\frac{1}{2}$ mean horizontal + $\frac{1}{4}$ maximum. This gives only approximate results, but can be used to save the trouble of making a large number of photometric determinations.

Relation of Light to Current. — Investigating the factors influencing the amount of light given off by the arc, Violle found that the quantity emitted by a unit surface of the crater was the same, whether the arc current be 10 or 1,000 amperes. This was to have been expected, since the crater cannot be heated beyond its point of volatilization and still remain in the solid state. The light is therefore roughly proportional to the area of the crater. The spherical candle-power is also approximately proportional to the total number of watts utilized in the arc, but is of course affected by anything that varies the efficiency.

Efficiency. — By the efficiency of the arc is meant the ratio of the luminous flux to the total heat and light radiation. Anything

that tends to dissipate the energy at any place other than the crater of the positive carbon diminishes the efficiency.

The arc is the most efficient source of illumination known. The most generally accepted value for its efficiency is 13 per cent. The corresponding figures for the other sources of light, are for the candle $1\frac{1}{2}$ per cent, the gas-flame 1 per cent, the Welsbach light $2\frac{1}{2}$ per cent, and the magnesium light 12 per cent.

The efficiency of the incandescent electric light is about 5 per cent. These values are comparative but probably too high. Among the causes that modify the efficiency of the arc are these:

1. The structure, density, and composition of the carbons. These affect both the volatilization point, and hence the temperature, as well as the thermal conductivity upon which depends the amount of heat conducted away by the carbons, which is lost energy. Purity, softness, and evenness are desirable.

2. The cross-section of the carbons. Large carbons conduct and radiate more heat than small ones for equal currents, hence for a given current the efficiency diminishes about inversely as the diameter of the carbon increases.

3. The existence of a soft core reduces the temperature of the crater, and tends to lower the efficiency.

Current and Voltage. — The division of the watts at the arc into current and voltage is extremely important, depending on various factors not yet understood. Carhart found that with 450 watts at the arc, made up of 10 amperes and 45 volts, he got a maximum candle-power of 450; while with the same number of watts in 8.4 amperes and 54 volts he obtained 900 maximum candle-power, just twice as much. Blondel, however, finds the luminous flux greatest usually below 45 volts. The discrepancies are probably due to differences in size and quality of carbons, because there is naturally a certain current density for each carbon, which gives the best results.

Commercial Values of Voltage and Current. — The value of 45 to 47 volts at the arc, reached after years of commercial experience, is probably the best. At this point the efficiency is high, and the conditions are about half-way between hissing and the flaming points. At this voltage, too, as the curves show, the voltage at the arc is only slightly affected by fluctuations in the current strength. *Ordinary current values* range from 6.5 to 10

amperes for long arcs in air. Greater voltage is inadvisable, as it reduces the number of arcs that can be placed in one series, increases carbon consumption, tends to produce flaming, and introduces too much energy in a single-light unit.

Less current than 6.5 amperes gives too little light for a unit, used under conditions suitable for a series circuit. On constant potential systems small open arcs of low current have been attempted, but without much success. The low current arc has a large cooling surface for the energy used. If for some of the reasons given later in detail, the current in the arc falls, the proportion of the cooling surface to the energy is greatly increased, in fact to such an extent that the arc flickers violently or is put out by the chilling effect. Where arcs are inclosed in *heat-retaining bulbs*, the current may be greatly reduced before this effect takes place.

Composition of Light. — The composition of the light of the arc has been determined by Meyer to be as follows, where the intensity of the yellow light is expressed by unity. Red and orange 2.09, yellow 1.00, green 0.99, blue 0.87, indigo 1.03, and violet 1.21. Taking the intensity of red as 100, Abney gives for direct sunlight; Red 100, green 193, violet 228; while for arc light his figures are: Red 100, green 203, and violet 250. For gas-light he found the values to be: Red 109, green 95, and violet 27.

The composition of the light of the arc may be, however, greatly changed by the hardness of the carbon, the material of the core, and by the current and voltage. Hardness usually determines the maximum temperature of the crater, while the current and voltage alter the proportions of the light fluxes coming from the yellow crater and from the violet arc stream. The vapor of the core acts to color the light as well as to determine the volatilization point of the crater.

The color of the arc light approaches very nearly to sunlight, and it has the remarkable quality of producing a similar sunburn. Great caution is necessary on this account in avoiding exposure of the eyes to the arc at close range, otherwise a painful sunburn of the eye, producing a tedious inflammation, is apt to result. This can be avoided only by protecting the eyes *on all sides* with leather goggles fitted with smoked glasses.

Short Arcs. — In the earlier days of arc lighting, so-called "short" arcs were employed, taking 18 or 20 amperes at about 25 volts with an apparent arc length of $\frac{1}{50}$ to $\frac{1}{25}$ of an inch. The object of such a short arc was to increase the number of arcs that could be operated in series by a given voltage. Owing to the large current, the carbon consumption was high and the line drop excessive, so that these causes, combined with the frying sound and delicacy of regulation required, have brought about their abandonment. The long arc now employed in open arc lamps has roughly half the current and double the voltage. The carbon carried off the positive by electrolytic action is of course only half as great; but the longer arc affords more opportunity for the air to oxidize the carbon, so that the carbon life in the long arc is not proportionately increased,

Unstable Arcs. — Between the condition of a short arc and a long arc there lies a zone of instability for which the probable analogy is the concussive boiling of water on the dividing line between the stage of rapid evaporation and quiet ebullition. After the long arc is reached, it is necessary, in order to maintain a fixed voltage at the arc, to increase the distance between the electrodes as the current increases. The difference in the relative life of the carbons in the long arc and in the short arc is quite marked. In the short arc the positive wastes away rapidly owing to the heavy current, while the deposition of carbon on the negative is almost sufficient to prevent waste; besides which the air currents have not sufficient room to form in the short arc.

Blowing Out of the Arc. — A peculiar feature of all arcs is their liability to be blown by a strong gust of air unless fed by a constant current machine which cannot fail to maintain the current. A magnet will also blow out an arc if the pole is brought sufficiently close. This magnetic action, as previously stated, causes the bow shape characteristic of the arc, and in the case of an alternating current causes the arc stream to rapidly bend from side to side across the earth's line of force. The blowing-out tendency of the magnet is frequently employed to direct the arc upon metals for the purpose of melting or heating them, as well as in various magnetic blow-out devices, in which the blowing-out effect rapidly extinguishes an arc formed between two contacts liable to be melted by the continued action of the current.

Arc on Constant Potential Circuits. — When arcs can be run in series on circuits furnished by constant current machines they have the great advantage of having the current maintained as long as the arc is not cut out of the circuit, so that irregularities in the arc or mechanism produce only a variation in the intensity of the light, but the illumination, good or bad, is always maintained.

It is, however, often desirable to run arc lamps on constant potential mains at the usual 110 or 220 volts pressure, where the current is no longer constant unless a device is introduced to make it so. Every constant potential arc lamp has a mechanism of this kind contained in the case whose function is to separate the carbons when the current is too high, and bring them together when it is too low. If well made and adjusted, such a regulator may respond to current variations of five per cent either side of the value at which it is set, which might be expected to maintain a practically constant current. Such, however, is not the case. An arc whose carbons are fed by a mechanism of this kind, *if connected directly* to a constant potential main, will behave in the most erratic manner, even if it be started by hand regulation, and allowed to warm up before the test. The mechanism adjusted to respond to five per cent current variation now utterly fails to keep the current anywhere nearly constant, and the arc is very unsteady. This is true even if the voltage of the mains corresponds to the voltage desired at the arc.

The reason for it lies in the fact, shown by previous curves, that the resistance of an arc decreases as the current increases, which results in a tendency for the current to become almost infinite if constant potential is maintained across its terminals. Similarly, if the current begins to decrease, and so lessen the cross-section of the arc, the resistance rises and further chokes off the current, until the arc goes out. The arc when directly connected to constant potential mains is therefore in a state of unstable equilibrium, in which the current tends to drop to zero or surge toward infinity. This action, depending as it does only on the instantaneous cross-section of carbon vapor at any moment, is itself instantaneous. The mere inertia of a mechanism retards it so much that the arc is out before the regulator has perceptibly moved. The means used to counteract the instability of the arc must operate as fast as the current change can take place. Such an auxiliary

regulator, although an inefficient one, is made by the simple expedient of inserting a series resistance between either side of the arc and the mains.

The mechanism keeps the average current constant by *increasing or decreasing the length* of the arc. The resistance overcomes the tendency toward rapid fluctuation by automatically and instantaneously *raising or lowering the voltage* across the arc gaps as required. As an illustration, assume an arc to be connected to constant potential mains of 40 volts, and the regulating magnet to be wound to pass 10 amperes with a normal length of arc. If for some reason the current suddenly drops to 8 amperes the resistance of the arc rises, though its length may not have changed, and it requires more than 40 volts to bring the current back to 10 amperes and maintain it, therefore the arc goes out. If now we connect the same lamp in series with a one-ohm resistance to a 50-volt circuit, the current again 10 amperes, the lamp will have 40 volts at the terminals as before. Now let the current fall to 8 amperes. The drop through the resistance is only 8 volts, and we have $50 - 8 = 42$ volts at the arc, which is sufficient to force more than 8 amperes through it, and so restore the current to the normal 10-ampere value. The resistance in series is sufficient when the rise of voltage at the arc, caused by less drop in the resistance, suffices to force the original current through it, in spite of its diminished cross-section. If too little resistance is used, a given decrease of current will not produce sufficient rise of voltage at the arc to maintain it, and it goes out. If too much resistance is employed, the rise of voltage at the arc is excessive for changes of current too small to move the mechanism, and the lamp tends to allow the current to surge beyond its proper limits. This regulating or steadying action of resistance is of course instantaneous, as it depends on electrical changes and not on inertia or mechanical motion. To a certain extent self-induction may have a similar tendency to raise the voltage at the point of rupture or increase of resistance in an electric circuit.

No Resistance in Series with Series Lamps. On series- or high-tension circuits resistance is not required, because the current is maintained, whatever the changes in the arc, by the inherent regulation of the dynamo. It is impossible, therefore, for the current to fail while the machine is in operation.

Constant Potential Lamps, Two in Series. The usual voltage of constant potential circuits being double that required for one open arc lamp with its resistance, being 110 volts or thereabouts, open arcs on these circuits are commonly connected two in series. If only one lamp is used, and the remaining excess of 60 or 70 volts taken up by resistance, the regulating action of the latter tends to make the light vary up and down slowly, as explained above. On circuits with a higher voltage than 110, more lamps are run in series, as for instance, 10 lamps in a string across a 500-volt circuit. From what has been said, it will be evident that both current and voltage vary somewhat in the arc on constant potential or incandescent circuits, while voltage alone varies on a good series circuit. A carbon that will tend to produce a steady light, such as a cored carbon, is, therefore, advisable for constant potential lamps. Again, these lamps are commonly used for interior illumination, so that a better grade of carbon and one that produces a softer yellowish light is desirable.

Troubles in the Arc Proper. — The chief troubles found in direct current arcs not caused by the mechanism are these: —

Flaming, from too long an arc, or impure carbons, or half-baked carbons containing unexpelled gases. The flame usually runs up the side of the positive, accompanied by a drop in resistance and loss of light.

Hissing, due to too short an arc or too vigorous vaporization or too coarse-grained carbons. This is attended with loss of light, low resistance, and an objectionable hissing noise.

Sputtering, from impurities in the carbon, or loose-grained carbons.

Whistling, occasioned, as in a Chicago installation, by electrostatic induction between the underground conductors and their metal sheaths. These current vibrations reproduce themselves in variations in the volume of the arc stream, producing a shrill noise.

Traveling of the arc around the carbons producing unequal illumination and flicker. This arises from the tendency of the arc to continually seek the path of least resistance, which wandering increases with the area of the carbon over which the arc may travel, in other words, the area of the end. This may be remedied by the use of smaller carbons or of cored carbons, in

which latter case the soft core vaporizes first, and the arc is confined to the inner surface of the crater thus produced.

Bucking of arcs connected in series, owing to the mechanism of all the lamps endeavoring to correct a change of current due to the improper working of one particular lamp. This is frequently very marked on incandescent circuits, where only two lamps are in series. If one sticks, it frequently consumes all of the energy, leaving the other nearly dark. To overcome this, both proper design of the mechanism and proper adjustment are required.

Alternating Arcs. — When arcs are fed by alternating current the arc is no longer a continuous flame, but is lighted and extinguished at every reversal of the current. When these follow one another faster than 100 per second, corresponding to a frequency of 50 periods, the flicker is not apparent to most eyes. Owing to the reversal of the current each carbon acts as a positive at every other alternation. There is, therefore, no crater, both carbons remaining pointed, but the upper one wastes away 8 or 10 per cent faster than the negative, due to receiving the ascending heat.

Voltage and Current. Under commercial conditions, using cored carbons, open alternating arcs consume about 15 amperes at 30 to 35 volts. This would seem to be unaccountably less than that required for a continuous current arc using the same carbons; but it must be borne in mind that an effective alternating voltage of 35 has a maximum potential of about 50 at the top of the wave.

Function of Core and Object of Heavy Current. When the carbons are separated, it would appear that the first extinguishment of the arc as the current passed through zero would put out the light; but a continuous path is provided for the current by the bridge of incandescent carbon vapor that persists until the voltage acquires a substantial value in an opposite direction. To obtain this effect the current used in alternating arcs must be larger than in continuous current arcs, and the carbons are always cored, to insure a sufficient supply of carbon vapor.

Power Factor. If the current and *E.M.F.* are in phase the power at the arc in watts is the product of the volts and amperes. Steinmetz, however, has shown that since the apparent resistance varies with the current there must be a lag of current behind the electromotive force. Experiments show that the true power in

the open alternating arc is about 85 per cent of the apparent watts.

Wave Form. The efficiency of the alternating arc increases slightly with the number of alternations, and is considerably affected by the form of current wave, which is largely determined by the shape of the wave of *E.M.F.*; a flat-top wave producing a higher efficiency than a peaked one. This is because the flat-top wave creates less interruption in the flow of current than the sharp pointed wave, the latter allowing the carbon a considerable interval between maximum values in which to cool off.

Hum. A peculiarity of the alternating arc is its hum, corresponding in pitch to the alternations. It arises from the expansions and contractions of the arc stream with the current, producing corresponding vibrations of the adjacent air. This has nothing to do with the hissing sound that may occur from very short arcs as with the continuous current. When the alternating arc hisses, the voltage falls, but less abruptly than with the continuous arc, while the current lag is increased until the true watts are only 75 per cent of the apparent watts. The light emission of the alternating arc at any instant lags a little behind the curve of instantaneous value of the real watts. It never passes through zero, owing to the retention of heat by the carbons.

Efficiency. With the same energy and carbons the mean spherical candle-power of the alternating open arc is about one-half that of the continuous current open arc.

Distribution. The distribution of light is nearly equal above and below the horizontal, as shown by Fig. 267. Therefore the light going upward, which is nearly one-half, would be wasted were it not for the white reflector usually employed immediately above the arc to throw the light down.

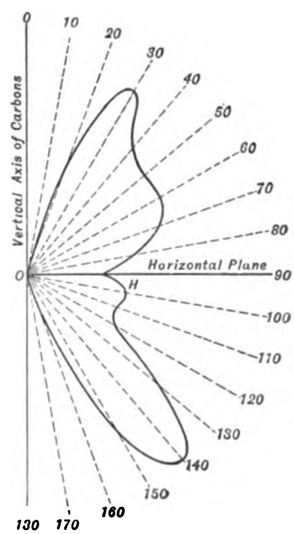


Fig. 267. Light Distribution, Alternating Current Open Arc.

Focussing Mechanism. The more equal consumption of upper and lower carbons in alternating lamps necessitates a mechanism

that will feed both carbons in order to retain the arc in the same place. See Fig. 268. Such lamps are usually connected to the secondary of a transformer through an inductive resistance, known as an *auto-transformer* or *economy* coil (see Fig. 269), or they may be connected directly to a transformer wound to deliver a constant current (p. 171). The possibility of substituting an economy coil in which little energy is lost for the wasteful resistance used on constant potential direct current systems, compensates in a large measure for the low efficiency of the alternating arc.

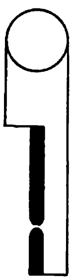


Fig. 268. Focussing. Mechanism.

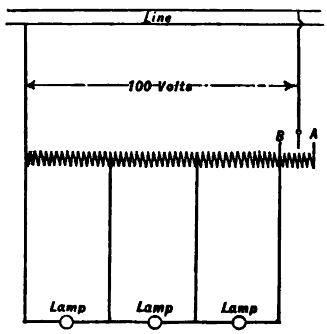


Fig. 269. Connections of Economy Coil.

Inclosed Arcs. — The rapid consumption of the carbons in the open arc led many experimenters to attempt to devise methods for reducing it. The earlier workers devoted themselves to making a compromise between the arc and the glow lamp, the general features of which were a minute arc formed at the point of imperfect contact between two carbons. These incandescent arcs were never successful for reasons now well understood.

About 1882, and in the years following, attempts were made to inclose the arc of the constant current lamps in air-tight globes of various sizes, but without success. In 1894 commercial lamps were successfully used, in which the arc was inclosed in a small globe or bulb of refractory glass protected by a larger outer one. It was found that the previous attempts to apply the inclosure to existing high-tension lamps with high current and low arc voltage was a step in the wrong direction, but that the inclosed arc was well suited to low current and high voltage arcs, which would be desirable on constant potential systems.

Inner Globe. The inclosing bulb is an egg-shaped globe about $5\frac{1}{2}$ inches long and $2\frac{3}{4}$ inches in diameter, tightly sealed below, and partially closed above. When an arc is sprung between the carbons inclosed in this manner, at first the same conditions exist as in

open arcs. The oxygen in the bulb is, however, rapidly consumed by combination with the carbon, and in six to ten minutes the bulb is filled with highly heated CO and CO_2. These gases would soon be replaced by air were it not for the arrangement of the cover of the bulb, which is usually ground to fit at the edges, with an opening in the center slightly larger than the carbon. This narrow annular opening, especially when corrugated internally, affords, by creating eddy currents of gases, great frictional resistance to the passage of the air, so that very little enters. The conversion of the air of the bulb into inert CO and CO_2 soon shortens the first long arc with 80 volts across to about $\frac{3}{16}$ of an inch. The combustion of the carbons by the oxygen of the air is now greatly reduced, so that the positive burns flat-ended, its loss being chiefly electrolytic. The positive is apt to have a slight tendency to become concave, while the negative tends to become convex, but both remaining approximately flat ended. Were it not for the air that seeps into the bulb the negative would not be destroyed at all, because not only is it not consumed, but it receives a deposit of carbon from the positive. It is found advisable, however, to admit just enough air to combine with the carbon vapor set free and burn it, to prevent it depositing as a black condensation on the bulb, or as a fragile nib on the negative. If pointed carbons are used in a bulb, they will become flattened after burning a short time.

Volts, Amperes and Watts. The usual energy at the arc in direct current inclosed arcs is about 400 watts (5 amperes at 80 volts). It is found that when less than 78 volts is used the carbon does not traverse a long enough arc to have its combustion completed, and with 50 to 60 volts, a deposit of this unconsumed carbon tends to form on the bulb, cutting off the light. When more than 80 volts is used, the carbon consumption is too high, the violet light from the arc becomes too prominent, and the arc has not sufficient resistance interposed in circuit with the usual 110 volts to keep it steady. The voltage between the electrodes being therefore fixed at 80, 5 amperes give the energy usually taken in lamps on these circuits. The inclosed arc has properties similar to the arc in air, the difference of potential increasing with the distance apart of the electrodes.

Hissing occurs for the same reason, but flaming is less, and the zone of flame is absent because there is no oxygen to support it.

Efficiency. The efficiency of the inclosed arc is not as high as that of the open arc owing to the fact that more energy is expended in the arc stream and less in the crater, and that the flat-ended carbons rapidly conduct away the heat, and that some 10 per cent of the light is lost in penetrating the bulb. The retention of the heat by the bulb, however, adds to the efficiency, so that the net difference in efficiency is probably not great.

Size of Bulb. Evidently a large bulb will be less efficient than a small one, and will also tend to produce a carbon deposit by chilling the vapor on its cooler surface. The size of the bulb affects the interval of unsteadiness which ensues when a lamp is started. The bulb being filled with air, which has diffused in since the lamp was last extinguished, the carbons are practically burning in the open air until the oxygen in the bulb is consumed. They therefore draw a long arc. After some time, depending on the amount of oxygen in the bulb, and on the tightness of the inclosure, the arc becomes unsteady; apparently because it is immersed alternately in atmospheres of carbonic oxides and oxygen, which greatly affects the arc's resistance. At such times the arc may be so unsteady as cut itself out. With small bulbs the change from the open arc to the closed arc conditions usually occurs in from three to five minutes, after which the light is steady. Generally speaking, the larger the bulb the longer the time before the arc passes through the period of unsteadiness.

Carbons. — The carbons employed in inclosed arcs must be straight and smooth, otherwise they will not pass freely through the opening in the gas cap. This precludes the use of molded carbons, which have an irregular seam running the whole length, and requires forced carbons, the difference being considered more fully in the beginning of the next chapter. The carbons must contain the minimum amount of impurity, as it is all deposited on the inside of the bulb, hence cored carbons are not suitable. Uniformity in diameter is essential.

The consumption of carbon in an inclosed arc is different in various positions in the bulb, chiefly owing to being more or less exposed to air currents. The greatest consumption is usually found to exist near the bottom of a bulb, and the smallest somewhere in the upper portion.

The ratio of the consumption of the *upper* to that of the *lower*

varies curiously in different portions of the bulb and in different lamps, usually between 15 to 1 and 2 to 1. If the inclosure were perfectly air-tight, the negative would hardly be consumed at all, or might even grow larger, whereas the positive would be consumed electrolytically nearly as fast as usual. The ratio might easily be 100 to 1 or 1,000 to 1 in such a case. Where, however, the air has free access to the arc, the consumption by the air may be as large as by the current, and we should then have a ratio of about 2 to 1 for positive and negative carbons respectively.

Rupturing the Arc. Inclosed arcs have a peculiar tendency to "cut out," or break the arc, which is not found in open arcs. This is apt to occur when a gust of fresh air enters the bulb and strikes the arc, cooling it and instantly changing its resistance. The arc has a tendency to travel around the large flat ends of the carbons, which produces the effect of a flicker, owing to the shifting shadow of the negative. This is less noticeable in open arcs whose pointed carbons center the arc. Inclosed arcs will also operate with much higher voltage than 80 across the arc, provided that approximately the same percentage of drop is retained in series with it. Thus 150-volt arcs on 220-volt circuit taking $2\frac{3}{4}$ amperes are often used, but give a more violet light.

Series Inclosed Arcs. — Considerable difficulty was first experienced in applying inclosed arcs to series high-tension circuits. On such circuits the current is often already fixed by the winding of the existing dynamos, the majority of which are wound for 6.8 or 9.6 amperes. If inclosed arcs, taking not less than 70 volts, were substituted for open arcs, taking 47 volts, the central station would have the number of lights on the circuits greatly reduced without a corresponding increase in revenue. Another objection is the heavy current, which has a tendency to overheat and soften small bulbs. Still another disadvantage is the length of time required to effect the short circuiting of the lamp by an automatic cut out when the carbons fail to feed or are consumed. With open arcs, the carbons burn so rapidly that the cut-out coil shunted across the arc acts in a few minutes, owing to the rise of the voltage across the arc. If the same construction were used, it would require about twenty times as long to effect the same action in the slow burning inclosed arc, so that the high-resistance cut-out coil, which is made of very fine wire, is liable to be damaged

by the prolonged passage of the current through it. But these objections have now been overcome. The demand for inclosed arcs on series circuits was not at first so keen as at present, owing to the cheap carbons used and the rough quality of the light allowable for exterior illumination, in which efficiency is highly desirable and absence of glare not so much of a consideration.

Advantages of Constant Potential Inclosed Arcs. — The rapid introduction of inclosed arcs on incandescent circuits in the last few years is due to the many advantages which they possess compared with open arcs on the same circuits. First, perhaps, is the saving effected in carbons, which last from 100 to 150 hours per pair on the average, with proper adjustment. Ordinary open arc carbons last about 8 to 10 hours. In fact, inclosed arc lamps are usually designed so that the remnant of the positive carbon may be used as a negative on the next run, if cut to the proper length. Longer life than 100 to 120 hours is probably not desirable in inclosed arcs, because it is obtained at the expense of an excessive deposit on the sides of the bulb, and a sacrifice of efficiency and steadiness from carbons of increased diameter.

The long life of the carbons saves not only the value of the carbons themselves, but the greater labor-expense of retrimming. The nuisance of the daily visits of a lamp-trimmer, required for open arcs, especially in places where dust or a ladder is objectionable, has had a great deal to do with the favor with which the inclosed arc has been received.

The ability to light or extinguish one lamp at a time is important; because it effects an economy over the system of open arcs, in which two in series are always thrown on or off together.

Quality of Light. Absence of sparks is another feature secured by the inclosing bulb. The mechanism also admits of the utmost simplicity in its construction. The color of the inclosed arc, with proper combinations of globes, approaches very closely to daylight, since it is possible to cut out the undesirable parts of the spectrum by the use of glass of the correct shade. With clear bulb and globe the light is a violet tinge, which is not as pleasant as the modified color. The opalescent inner bulb usually employed acts also to diffuse the light, so that no violently luminous spot exists, but the light comes from the large surface of the bulb. The effect of this is to prevent sharp shadows, and to allow the pupil of the

eye to open wider without the sensation of glare; thus increasing the apparent illumination.

Distribution. The distribution of the light in a vertical plane has been investigated by Messrs. Freedman, Burroughs, and Rapaport, whose results are quoted herewith. They found that the distribution in an inclosed arc lamp is not the same as in an open arc lamp. See Fig. 270. The maximum in the former is at an angle of 25 degrees below the horizontal, instead of 40 degrees. The intensity, after decreasing, reaches another high value at 40 degrees, but not as great as at 25 degrees. The probable explanation of this peculiar form of curve is, that at 25 degrees the light comes obliquely from the crater, but is not cut off by the negative. Descending, the negative cuts off more light; but the rays emanate more perpendicularly from the surface of the crater until another maximum is reached at 40 degrees. The reflection from the bulb, and the position of the arc in it, would also alter this distribution.

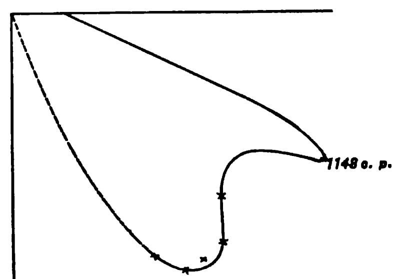


Fig. 270. Light Distribution, Direct Current Inclosed Arc.

Efficiency. Tables XI. and XII. (Freedman) show the effect of a clear and an opalescent inner globe, the same being shown graphically in Fig. 271. The same investigators measured the loss by opalescent outer globes, which they found varied from 35 to 50 per cent, and which occasionally is as great as 60 per cent. They conclude that with currents of 5 amperes and with two clear glass globes of the best quality the watts per candle are about .5, with opalescent inner and clear outer, the watts per candle are about .6, and with both inner and outer opalescent globes the watts per candle are about .95, being mean hemispherical candle-power in all cases. Holophane globes, whose construction is explained on page 334, gave the same loss of light as clear globes.

Whether the run is *continuous* or *intermittent* will make a difference in the life, although only slight. Theoretically the life should be less for the intermittent test that when the lamp is kept burning without any stops, and this is found to be the case. The stoppage allows fresh air to get into the bulb each time, thus

increasing the consumption. When the current is thrown off a lamp, it is noticed that the carbonic oxide gas ignites with the in-rush of air, and by a series of minute explosions causes a chattering of the gas-cap. Sometimes it burns with a quiet blue flame that lasts for five or ten seconds. To find theoretically the amount of carbon consumed with intermittent use we can calculate the weight of oxygen the bulb contains when filled with fresh air, and from this determine the amount of carbon burned before the

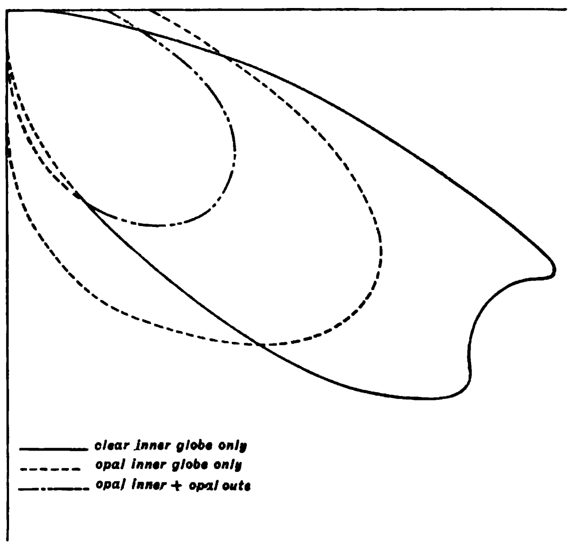


Fig. 271. Light Distribution, Inclosed Arc with different Globes.

TABLES XI. AND XII. (FREEDMAN.)

ANGLE FROM THE HORIZONTAL.	CLEAR INNER GLOBE. CANDLE-POWER.	OPAL INNER GLOBE. CANDLE-POWER.
20 above	89	152
10 "	82	184
0	139	347
10 below	501	455
20 "	980	735
25 "	1397	
30 "	1300	985
40 "	1355	1050
50 "	1060	969
60 "	674	855
70 "	414	734
Mean Hemispherical	850	770

admission of any more fresh air. Taking 4 hours as an average run, a lamp burning 140 hours would have 35 stops, equivalent in consumption to 5 hours run, and on this basis would consume carbon as if it had burned continuously for 145 hours. An air-tight outer globe will increase the life; but it has a tendency to raise the temperature of the interior sufficient to warp or interfere with the action of some of the parts, although it will not do so with proper construction.

Alternating inclosed arcs have also reached a high state of perfection. In principle they are similar to the inclosed arcs for direct current. The essential difference is in the use of one or both cored carbons, with consequently lower voltage and greater current.

With solid carbons the long arc has a tendency to be extinguished, and the vapor supply of a core is required to maintain the conducting medium between the electrodes. Owing to the inclosure, which gives a stability and freedom from interference of air currents, it is sufficient to use one cored carbon, and it is of course indifferent whether this be the upper or the lower. It is not advisable to use two cored carbons, for reasons explained in connection with continuous current arcs, namely, the efficiency is more or less sacrificed, and the deposit in the bulb is increased.

The length of arc is greater than in the direct current lamp, being about $\frac{3}{8}$ of an inch. At the start the arc may be as long as $\frac{1}{2}$ to $\frac{5}{8}''$ before the air in the bulb is consumed, or the resistance up to its maximum value. When hot, the usual current is 6 amperes, with a voltage at the arc of 70 to 75 volts. With 70 volts and 6 amperes in a 104 volt circuit, the apparent watts at the lamp terminals are 625 and at the arc 420, the actual watts being 445 and 390 respectively. The watts consumed in the inductive resistance average 35 to 45. This resistance usually consists of a coil in series with the arc wound on a laminated iron core, and mounted in the trimming of the lamp. By connecting the terminals to different portions of this coil, the reactance may be greatly varied, so that the lamp is capable of a wide range of adjustment for various circuits. As a rule the reactive coil can be adjusted to maintain 75 volts at the arc for circuits varying in voltage from 100 to 125, and in frequency from 60 to 133 cycles per second.

A striking advantage of the inclosed alternating arc is its freedom from the hum that characterizes open alternating arcs. This is due to two causes. In the first place, the mere inclosure in a fairly well-sealed bulb reduces the noise, but the action of the bulb in keeping the gases hot is the more potent factor. It will be recalled that in the case of the open alternating arc the hum was produced by the rapid expansions and contractions of the arc stream following the waves of current. When, however, the arc is surrounded by a heat-retaining envelope of glass, the gases at the arc do not contract as violently with its instantaneous extinguishment, hence the amplitude of the vibrations, and the consequent hum, are much reduced.

Another source of noise in alternating lamps was the vibration of the laminated iron of which all magnetic parts are constructed. The thin sheets alternately repelling each other, and losing the repulsive force, are sent into violent vibration, which readily communicates itself to the whole lamp, with an effect like that of a sounding-board.

Since by the modern method of inclosure the noise of the arc itself has been nearly eliminated, corresponding efforts have been made to reduce the hum of the iron. By clamping the core of the reactance coil and magnet cores at a great many points, the iron is held too firmly to vibrate. The iron parts are then supported entirely on springs and rubber, both in light compression, so that the vibrations are not communicated to the lamp frame. Tight inclosure of the whole lamp completes the deadening effect, so that modern alternating arcs are made nearly noiseless.

The life of the alternating arc as usually constructed is much less than that of its continuous current congenitor. Owing to the complication in the mechanism caused by feeding both carbons simultaneously, and the difficulty of feeding through both ends of a bulb, the alternating inclosed lamp is usually constructed so as to feed only the upper one. But in an alternating lamp both carbons are equally consumed, and it becomes necessary either to make the lower carbon excessively long or to shorten the life. The latter is considered preferable, and the average life is about 80 hours with ordinary inclosure. For this an upper carbon of $9\frac{1}{2} \times \frac{1}{2}$, and a lower one of $6 \times \frac{1}{2}$ inches are usually employed.

CHAPTER XV.

ARC LAMPS.

Carbons. — *Manufacture.* The performance of the arc light is so largely dependent on the quality of the carbons employed that some knowledge of their method of manufacture is of great assistance. Many of the discrepancies that have been found in laboratory experiments and commercial work are due to the fact that different kinds of carbons were employed.

Carbons are of two kinds, according to their mode of manufacture, molded or forced. The molded carbon, as its name implies, is shaped in a steel mold. The forced carbon is squeezed while plastic through a circular orifice. The preliminary stages of treatment being similar, a single description will suffice for both.

Various materials have been employed; but the most prominent is petroleum coke, which is a product obtained in the distillation of paraffin. Other materials, such as gas-coke, lamp-black, are also utilized for this purpose. The material is first crushed, then placed in retorts heated to a high temperature for 10 to 50 hours according to the result desired, thereby driving out moisture, and imparting the quality of conductivity. The carbon is next ground to a fine flour in mills, and then bolted. The carbon flour thus produced is put in mixing kettles or pans combined with the "binding material" consisting of pitch which has previously been crushed. These pans are kept warm, and the entire mixture is constantly stirred by hoes or other means for a period of fifteen minutes to an hour. The heat causes the particles of pitch to attach themselves to the particles of carbon. The mixture is then cooled, and again crushed, ground, and bolted, so that a flour of uniform grain is produced.

Molded Carbons. From this point the treatment of the material depends upon whether *molded* or *forced* carbons are to be produced. If the former, the material is brought to men

working at benches, and provided with steel molds. These are split in halves, being grooved according to the length and diameter of the carbon cylinders to be made. The molder weighs the flour in a scale, distributes it evenly over the surface of the mold, and places the steel cap upon it. The mold is then slowly heated in an oven, which causes the particles of combined pitch and carbon to become pasty. When the proper degree of heat is reached, the mold is taken from the oven, and placed under a hydraulic press, the pressure employed varying between 100 and 400 tons. From the press the molds are taken back to the benches, the cover and sides removed, and the "card" of carbons carefully lifted out. When they become cool they are separated from each other; and the little "fins" that have held them to their neighbors are scraped off each side, so that each carbon is left a fairly perfect cylinder. For lamps fed by a constant direct current, carbons are usually made by the molded process, to which they seem best adapted.

Forced Carbons. — Arc lamps for constant potential or alternating currents require a carbon whose particles are arranged differently from those in the molded process, and also in many instances a core of less dense material to insure steadiness of light. The flour for carbons to be made by this process is treated somewhat differently from that of the molded variety. It is usually shaped into cylindrical "plugs" about 6 inches in length, and from 2 to 6 inches in diameter. These are placed in front of the plunger of a hydraulic press whose action is horizontal, and are forced through its jaws, taking any desired cross-section from the outline of the die at the mouth. As fast as the carbons issue from the die, they are received upon a table, and cut to desired length. In order to make them "cored," a hole about $\frac{1}{8}$ of an inch in diameter is left in the center of the carbon as it passes through the die, by the action of a "tongue," projecting into the orifice of the die from the inside. There are various combinations for the mixture that is used to fill the core, and the secret of its composition is usually guarded by manufacturers. This point in either process is called the "green carbon" stage. They appear shiny black in color, are quite heavy, break easily, and when held in the fingers, and tapped together, give only a dull sound. Both molded and forced carbons are next taken to

the furnace-room where the volatile matter contained in them is driven off. This is a process requiring great care. If they are baked too rapidly, they warp, and are hard to adjust in the lamps. If they are not baked sufficiently, they are too low in conductivity, and give a very poor light. In some cases the baking is performed in fire-clay pots, this being the process employed by many foreign manufacturers. In this country it is customary to lay the carbons in a large rectangular furnace, layer upon layer, separated by beds of sand, the entire mass protected by a covering of sand several inches in thickness, and subjected to heat until every carbon has reached a high temperature. The total time occupied is very considerable, being often one or two weeks from the time the charging begins until the process is completed. From the furnace the carbons are carried to the sorting-tables, where they are tested by rolling them on steel plates of true surface in order to separate the straight from the crooked ones. Some of the latter are sold as seconds, others are cut into short lengths, and the worst ones are rejected. Even in the best imported forced carbons there are often found from 2 to 5 per cent of badly warped carbons.

Molded carbons differ from forced carbons in many ways. They have a loose granular structure that runs lengthwise through the carbon, at right angles to the line of pressure. They also have the remnant of the web that holds a card of carbons together; and even if this is ground off, the surface is not perfectly cylindrical. Impurities are more likely to be found in molded than in forced carbons, and they are not as uniform as the forced article. They are used in series constant current lighting chiefly, where cheapness is the greatest consideration.

Copper plating these carbons is often resorted to, with the objects of increasing their conductivity, especially at the point of contact with the clamp, and prolonging their life. The copper sheathing protects the carbon near the arc from oxidizing so rapidly, and a $12'' \times \frac{5}{8}''$ coppered carbon in a 10-ampere lamp will burn about 14 hours, whereas the plain carbon of the same make will not last more than 12 hours.

The forced carbon is usually a higher grade of carbon than the molded, especially those imported from Germany and Austria. The texture is finer, and the material softer, than in the molded

form, while the grain runs transversely or at right angles to the line of pressure. Owing to the method of manufacture such carbons are more easily made to a given diameter, and are more uniform in diameter, structure, and straightness than the molded carbon. They have a comparatively high conductivity and are not copper plated. They are used for cored carbons particularly. The high grade and pure forced carbon more nearly resembles lampblack, and will make a mark on paper like a pencil, whereas the hard forced carbons will not. Where carbons are held by a small clamp far from the active end, and must fit closely but freely into an opening little larger than the carbon itself, too much stress cannot be laid on the necessity of securing straightness and uniformity. All carbons contain impurities, chiefly silica, iron, and smaller quantities of other substances. In the highest grade of imported carbons the silica is the chief impurity, with little else, but chemically pure carbons have not been produced by any manufacturer.

Carbons may be cut to any desired length by nicking them all around and breaking them as one would a glass tube. In inclosed arcs and in alternating arcs both carbons are the same size, whereas in focussing high-tension lamps and in open arc low-tension lamps, the upper carbon is usually about $\frac{1}{8}''$ larger in diameter than the lower. The only carbons that are copper-plated are those used in high-tension, series, constant current lamps.

Globes. — The glassware used to inclose the arc has received little scientific attention heretofore, and it is not at all unusual to attempt a five or even one per cent saving in generating the current, and allow a 30 per cent loss in its utilization to go neglected. Globes are made of three materials, clear glass, opal (or opaline or opalescent) glass, and a combination of the two called alabaster. Arc lamp globes are either blown or molded. If the former they will vary in regularity, some being thicker, more or less curved, etc., than others. Often the mark of the tool used by the glass-blower to shape the globe as he turns it will produce streaks. Molded globes are quite regular, but frequently show the joints running vertically down the side of the mold. Clear glass globes when clean, thin, and of good quality transmit 90 to 95 per cent of the light. When dusty, thick, or of poor glass the loss is easily doubled. The most common defects in these globes are bubbles,

ribs, and other inequalities which cast shadows, and render the illumination very uneven.

Opal globes are made of a glass into which some substance, frequently iron, has been introduced, making it translucent, but partly destroying its transparency. This is done to diffuse the light, and to cut off certain undesirable colors. The globes will vary from one through which outlines can be readily distinguished, to those whose appearance resembles a china plate. The denser globes effect a greater diffusion, but frequently cut off the greater part of the light. A light opal globe may cut off 20 to 35 per cent and a heavier one from 35 to 50 per cent.

Alabaster globes are made of two layers of glass, one clear and the other translucent. They are usually very dense, and cut off 40 to 60 per cent of the light. In order to combine the high transmissive power of a clear globe with the diffusion of an opal one, it is customary to grind clear globes, dividing the surface into equal portions. The dividing line may be either vertical or horizontal. The former is usually employed where the light is to be thrown in a direction away from the spectator, as, for instance, into a show window from a lamp hung in front. The horizontally half-ground globes are often used for the illumination of large interiors where an intense light is to be thrown on the ceiling and upper walls for diffusion and a less glaring light to the floor below. The effect of the grinding, which is usually done by a sand-blast applied to the outer surface of the globe, is to diffuse the direct rays of the arc, and form a brilliant scintillating surface. When the roughening is caused by acid the effect is less marked. When applied to both outside and inside of a globe the diffusion approaches that of light opal. A very successful effect for interiors is produced by grinding the lower two-thirds of the surface of the globes, thus cutting off the direct arc rays, even to those standing some distance away.

The general shape of arc lamp globes is such as to protect the arc from side winds, with less attention to inclosure from rain or snow. With open arcs the shape should be such that the globe is easily cleaned without removal from the lamp, not apt to crack from changes in temperature, and of such curvature that dust, insects, etc., fall into the cup usually placed beneath.

With inclosed arcs a shape which will not show a long, dark portion in the shadow of the negative carbon should be chosen.

The distribution of the light as well as its intensity is greatly effected by the globe used, largely owing to internal reflection.

The curves in Figs. 271 and 272 show approximately how the vertical distribution varies with different globes.

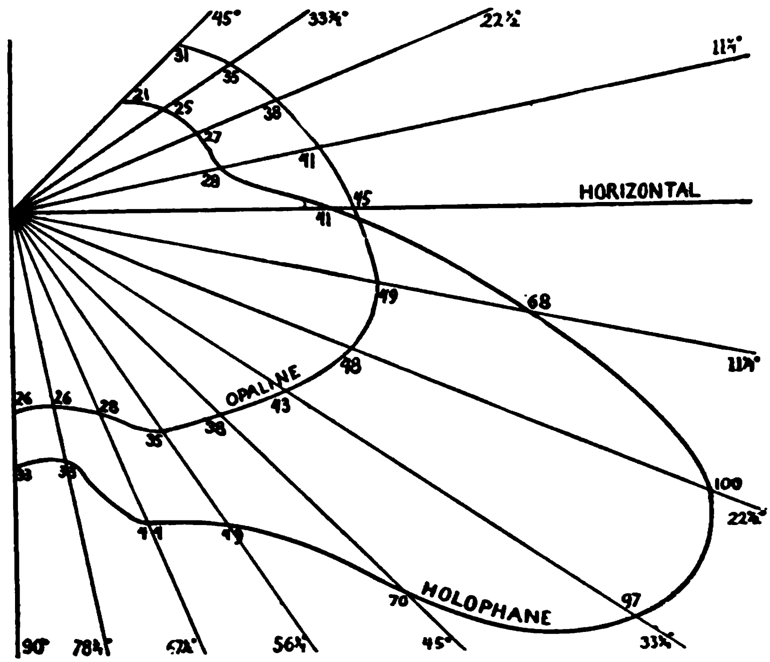


Fig. 272. Distribution of Light, D. C. Inclosed Arc.

Recently a new form of globe, the holophane (wholly luminous), made of clear glass after the designs of Blondel and Psarovdaki, has come into use. This globe diffuses the light perfectly, so that every part of the globe sparkles equally brightly, redistributes the light so as to throw downward many of those rays that would go upward or otherwise be lost, and is capable of varying the distribution to suit the purpose to which it is to be applied.

The distribution of the light is effected by prisms, whose section is somewhat like the teeth of a circular saw, molded in horizontal rings on the outside of the globe. The vertical section of a holophane, Fig. 273, shows that each tooth differs somewhat from its neighbor. The prisms on the uppermost portion of the globe are so designed that the rays striking them will be totally

reflected back through or nearly through the source of light, and emerge from the lower part of the globe on the opposite side.

About 45 degrees from the top, the prisms deflect the up-going rays, so that they emerge horizontally and somewhat below the horizontal. From there down to the level of the arc the prisms all refract and reflect the light down toward the floor or street. Below the horizontal the function of the prismatic ribbings is to distribute the light so that the objects below the arc are uni-

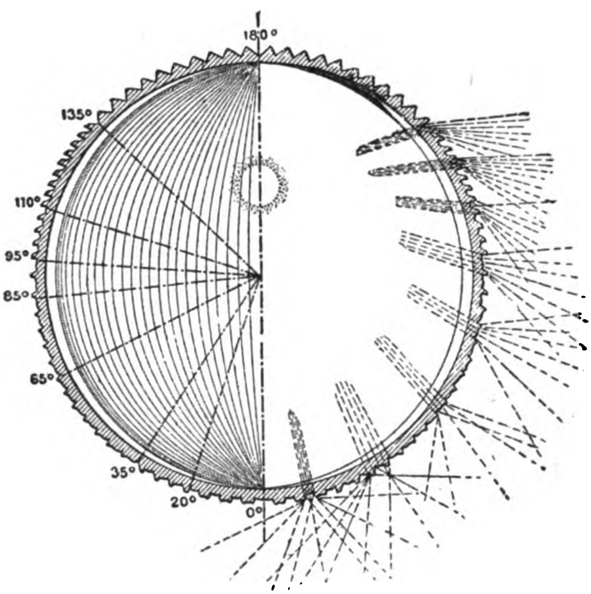


Fig. 273. Vertical Section of Holophane Globe.

formly illuminated, weakening the intensely bright zone due to the maximum candle-power about 40 degrees below the horizontal, and lightening the darker circle that tends to exist immediately below the lamp.

To secure still more perfect diffusion the globe is ribbed vertically inside, as shown by the horizontal section in Fig. 274. The effect of the diffusion is to make the outer edges of the globe, viewed from the side, appear as luminous as the center.

Holophanes have the disadvantage of requiring a stationary source of light to work to best advantage. This calls for a focusing open arc, or a fairly stationary inclosed one, two inches

variation in a 12-inch globe not being excessive. They have the disadvantages of being somewhat expensive, heavy, and harder to clean, but are a marked improvement over the old style in diffusion and economy of light. To show the care exercised in the design of the prisms, the manufacturers of holophanes in this country state: "The large holophanes have as many as 400 calculated faces, each designed for a special duty. The profile of each one of these prisms is calculated by the laws of optics, and drawn on a very much enlarged scale to secure accuracy. The drawing is then reduced and transferred, by a photographic process, to a

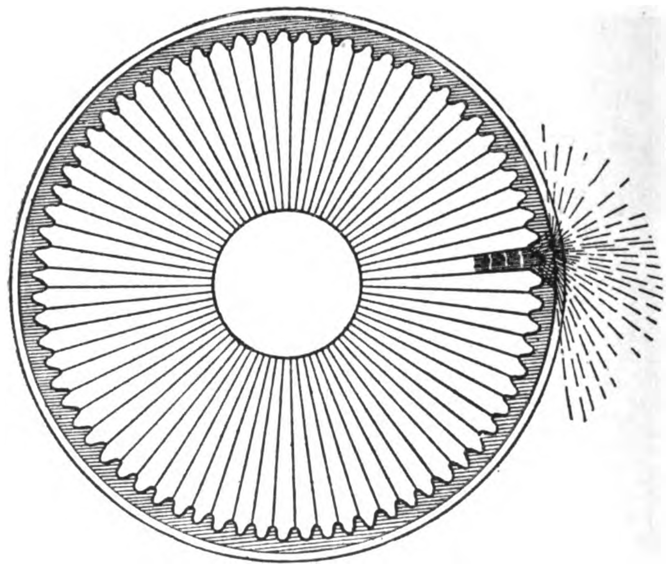


Fig. 274. Horizontal Section of Holophane Globe.

steel plate, and the profiles cut out with the accuracy of engravers' work. A tempered steel tool is then made corresponding to this template, accurate to the one thousandth part of an inch; and this tool is used in cutting the grooves in the mold in which the glass is pressed, after which it is annealed."

The cuts 275 and 276 show the effect of clear and opal globes on the distribution of light.

Lamp Mechanisms and Constructions. — The functions of an arc-lamp mechanism may be described as follows: —

1. To separate the carbons after having brought them into contact, if they were not together previously.

2. Maintain the distance between the carbons such that the energy at the arc is constant.

3. Feed one or both carbons together as they are consumed.

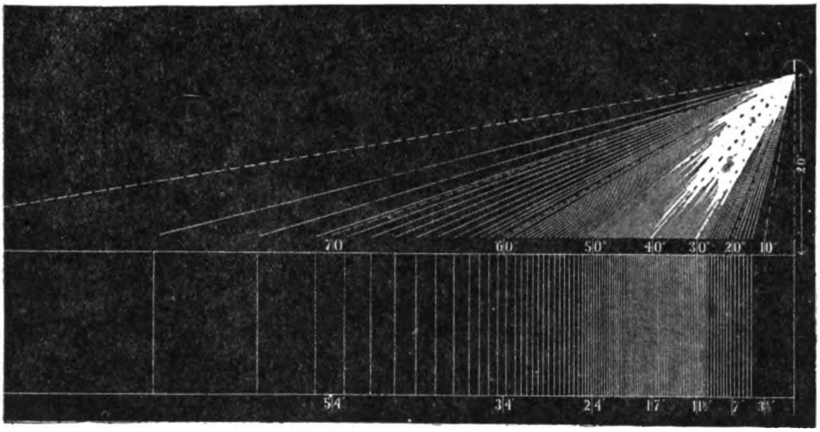


Fig. 275. Illumination on Street Surface from Open Arc.

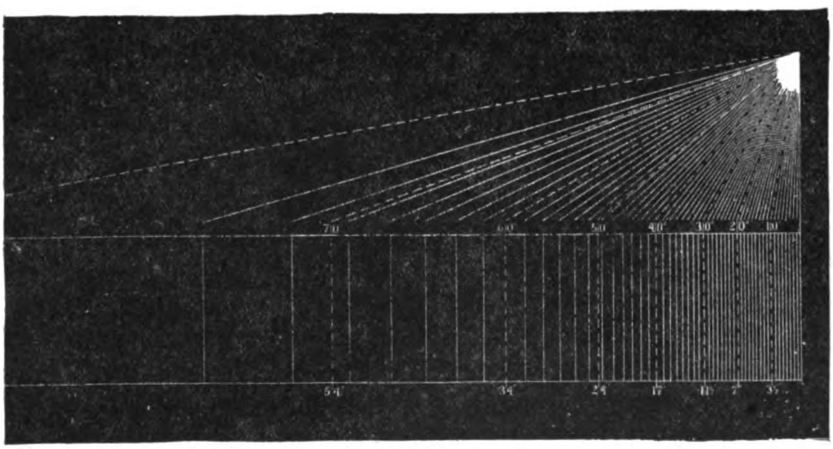


Fig. 276. Illumination on Street Surface from Opal Globe.

4. Leave the lamp in such condition when the current is turned off that it will resume operation when the current is renewed.

To these must be added another duty, dependent on the class

of circuit on which the lamp operates, usually effected by the "cut out" in one of the following ways:

5. On constant current circuits, to maintain the continuity of the circuit through another path, if that through the carbons is broken by failure to feed or by reason of their having been used up or broken.

On constant potential circuits to open the circuit under the same conditions if the lamps run in parallel, or to substitute an equivalent resistance if two or more lamps run in series.

Regulation may be by hand or automatic. Hand regulation is used where the operator is always present, as, for instance, with projection lanterns, searchlights, etc. For arcs employed for general illumination automatic regulation is invariably used.

The general principle employed is the balance effected between the pull of a spring, gravity, or both against the pull of one or more solenoids or magnets. The variations in mechanical details are endless. The balance is preserved when the arc is in its normal condition. The mechanism is so arranged that too great length of arc will weaken the solenoidal pull, and too short length increase it or *vice versa*. In lamps intended for series circuits, these functions are performed by two types of mechanisms, known as *shunt* and *differential*.

In shunt lamps a circuit is led to the solenoid from opposite sides of the arc, so that the normal voltage across the coil, whose resistance may be 400 or 500 ohms, is 47 volts for an open arc.

When the current is off, the carbons are held apart by the retractile force of a spring, gravity, etc. On turning on the current, a high voltage exists across the gap between the electrodes, and the solenoid overcomes the retractile force, feeding the carbons together. When the carbons touch, the voltage instantly drops, and the retractile force, overcoming the weakened solenoid, pulls the carbons apart, and springs the arc. When the voltage rises too high, the shunt coil again feeds the carbons enough to restore a balance. Two points are worthy of special attention in connection with shunt lamps. The first is that the carbons are apart at the start, introducing a very high resistance (450 ohms for each lamp in the series), unless there is an auxiliary cut-out circuit. This exceedingly high resistance introduces a difficulty in starting the average arc dynamo, and gives rise to potentials

exceeding the line voltage, and possibly dangerous. The other feature is that the mechanism is entirely independent of current strength, and will maintain a given voltage across the arc whatever the current. Therefore such lamps will operate on circuits of various current values without any additional adjustment. They have also the property of varying the energy, and therefore the light at the arc no more nor less than the percentage that the current varies from normal. On the other hand, when the current of a line abnormally increases, decreasing the resistance of the arcs, and tending to grow still larger, these lamps do not assist the dynamo to regain its equilibrium. This gives rise to a tendency to unstable equilibrium of the current in the line manifested by surging of the lamps or jumping arcs.

The differential lamp when at rest has its carbons *in contact.* They are separated by the pull of a series coil opposing gravity or a spring which the shunt coil *assists.* In this, as in the shunt lamp, the pull of the shunt coil tends to feed the carbons together. Obviously this lamp has a low resistance before the current is turned on, which is an advantage. The current passing through the carbons and series coil energizes the latter to pull the carbons apart, against the action of gravity, because the shunt coil is inert when the carbons are in contact with no voltage across them. This insures a rapid and positive opening of the arc. As soon as the arc is sprung, the shunt coil begins to act, but does not effect a balance until the series coil has pulled the arc long enough for the normal voltage. When the voltage rises, the shunt coil feeds the carbons exactly as in the shunt lamp. These lamps will work properly only within small limits on either side of the current to which they are adjusted. An increase in current will result in a stronger pull of the series coil, which will draw the carbons apart, until the increased voltage, acting through the shunt coil, again effects a balance; less current will weaken the series, and allow the carbons to approach. Such lamps therefore increase the apparent resistance of the arc as the current rises, and correspondingly assist the dynamo in maintaining the current value constant. For a given variation in current, however, they show a greater variation in light, since they increase the arc voltage with the current, so that the watts rise faster than the current strength. One point in favor of the differential lamp is that the striking of

the arc is a positive action effected by the current. Both styles of lamps give satisfaction, the most notable example of the shunt lamp being the Thomson-Rice, while the most prominent type of the differential is the Brush.

In addition to the elementary features above described, shunt lamps usually have an auxiliary shunt winding of coarse wire that acts in striking the arc. If the fine-wire shunt coil only were employed, the retractile mechanism of the first lamp to operate on starting up would separate the carbons without drawing an arc, since only a very small current can pass through the shunt coils of the other lamps in the series. The carbons will tend to vibrate, like the hammer of an electric bell, until all the carbons are down together, when they can all pick up their arcs. The coarse-wire shunt passes sufficient current around the carbons when apart to maintain an arc between the carbons of any other lamp in the series. As soon as the arc is struck, the circuit of the coarse-wire shunt is opened by the armature or an auxiliary magnet or some such device.

Cut-out. — In all *series* lamps it is absolutely essential to insert a device by which a continuous path is provided for the current in case the carbons fail to feed, or if they are totally consumed, or when the lamp is to be rendered harmless for inspection. In a circuit fed by a powerful arc machine the tendency to maintain the current is enormous; and an arc a yard long may be drawn at a potential of two thousand volts or more, unless some positive and reliable means exists for short circuiting it. These devices, known as cut-outs, are contacts connected to the poles of the lamps, and so arranged that they are brought together as required. Cut-outs should operate —

When the carbons fail to feed.

When the carbons are consumed or broken off.

When operated by hand by the trimmer.

The surfaces of the cut-out that make contact should be made of a metal not easily oxidized, such as silver, and with the surfaces vertical so as not to collect dust. A common form of cut-out is a silver button on the armature making contact with a fixed button, when the armature is pulled all the way over by the shunt coil. This practice is not to be commended, since it does not operate if the armature itself should stick. A better

arrangement is an auxiliary cut-out in addition to the armature cut-out, which will operate even if the armature sticks. The disadvantage of such a device is that it is liable to operate when not wanted, but this may be overcome by adjusting the auxiliary cut-out to act only at considerable increase over normal potential.

The cut-out that comes into play when the carbons are consumed consists usually of a contact attached to the carbon rod or parts moving with it, making connection with another contact on a fixed part of the lamp. To cut out the lamp by hand, a lever is frequently provided that will have the same effect as the descent of the carbon. In any case, the effect of a series cut-out is to dead short circuit the lamp, making it safe to handle.

On lamps that are run two in series on constant potential circuits, the cut-out must be set to introduce a resistance that will produce the same drop as the lamp itself, thus disturbing the other lamp or lamps in the same string as little as possible.

Inclosed arcs when run in series require a similar cut-out, but have none at all when burning singly in parallel on incandescent circuits. In this case the arc breaks when the carbons are exhausted, and the lamp goes out.

Long-range pull of magnets. It is evident that the magnets of all lamps must exert a pull on their armatures just sufficient to maintain a balance, whether the armature be close to or far from the pole. Where the force to be overcome by the armature pull remains constant, the magnet or solenoid must be constructed so as to have long range, that is, an even pull throughout the travel of the armature.

Where, however, the attraction of the coil for the armature is very unequal through the limit of motion, as it is apt to be unless specially provided for, the force of the armature is equalized over the range of the carbon motion by some mechanical device, called an equalizer, such as a pair of cams.

Temperature Correction. Another essential feature of modern lamps is an arrangement whereby the energy at the arc is maintained constant, independent of variations in the temperature, and hence current in the shunt coil. In shunt lamps this is usually effected by the somewhat expensive recourse to a special metal, with a low temperature coefficient, for the wire of the shunt. In differential lamps it is usual to shunt the series coil

itself with a small piece of low coefficient metal. When the shunt resistance increases through heat, weakening its current and pull, it would be overpowered by the series coil were it not for the fact that the copper series coil has also risen in temperature, shunting more current around itself through the low coefficient wire, and thereby weakening its own pull. By proper adjustment of this "temperature" shunt the lamp, whether hot or cold, may be made to maintain constant energy at the arc.

Magnetic Circuits.—The magnetic circuits of the shunt and series coils have an important bearing on the sensitiveness of the lamp. If the shunt coil is wound over or under the series coil, but in opposition to it, so that it has no separate magnetic flux of its own, increase in shunt current will weaken the pull of the series coil by a certain number of ampere turns. When, however, the series and shunt have separate magnetic circuits, and pull against each other, an increase in shunt current will draw the armature or core toward the shunt coil, shortening and strengthening its own magnetic circuit, and lengthening and weakening that of the series. This strengthens the pull of the shunt, while it weakens that of the series; the result being that the actions of the two coils are stronger and more positive when each has its own magnetic circuit.

The arrangement for feeding the carbons in arc lamps is usually of the non-focusing type when intended for service where the utmost simplicity of mechanism is essential. All street lamps were formerly non-focusing; lately, however, the care of electrical apparatus has become better understood, so that focusing lamps are quite practicable. The focusing arc lamp has several advantages over the non-focusing type. One of these is that the shadows of the side rods and bottom part of the lamp stay in the same place, and do not increase in size, as occurs when the arc travels downward on the negative carbon. Another advantage is that the heat is generated at the same point, and the globe is not unevenly heated rendering it liable to crack. The focusing arc also permits the use of a very efficient reflector, since the reflector can be placed and maintained close to the arc. (See Fig. 268.) In continuous current lamps this is not of such great importance, because most of the light is thrown downward anyway, but in alternating lamps it is quite essential. For use with holophane

globes a focusing lamp is important, since the holophane is designed to diffuse and distribute the light properly when coming from a certain specified point, preferably an inch or two above the center of the globe. If this point of light should travel downward, as it does in the non-focusing lamps as the negative carbon is consumed, the action of the holophane would be much less regular and satisfactory. The disadvantage of focusing lamps is the complication in mechanism required to feed the lower carbon, and the added difficulty of trimming. The lower carbon is usually drawn up by a chain passing around a wheel in the upper part of the lamp to the carbon-holder carrying the upper carbon. As the upper carbon descends, the lower one is drawn up, the action being regulated by a clutch working on some part of the wheel or chain mechanism. Another disadvantage of this type of lamp is the necessity for using carbons of different sizes. Thus a common combination is a $\frac{5}{8}$ inch upper carbon 14 inches long, and $\frac{1}{2}$ inch lower carbon 12 inches long, with a life of about twelve hours. If the lamps burn only seven or eight hours, as they do during a large part of the year, the remainder of the carbon is wasted. Whereas, in double carbon non-focusing lamps the same length of time would consume practically all of one pair of carbons. If it consumed more or less than an even pair of carbons, the remaining portion would be used to trim one side of the lamp, and a full set of carbons would be used in the other. Thus, no carbon is wasted, unless the lamps burn so long that more than one and one-half pairs of carbons are required; in this case of course it would be necessary to fully renew both pairs. Again, carrying two sizes of carbons in stock is somewhat of a nuisance for arc-light stations and lamp-trimmers.

Double Carbon Lamps. — Originally, in order to gain life, carbons were made very long, and were therefore expensive and liable to break. A pair of carbons some 12 or 14 inches long, of a size that will give good efficiency and steadiness, such as $\frac{1}{2}$ inch, will not last longer than eight hours; and this was found too short for all-night service during the American winter. To meet this need, Brush invented the double-carbon lamp. In this lamp there are two independent sets of carbons, both fed by one mechanism. The Brush clutch, which is shown in Fig. 277, is the device originally used to feed one pair until it was consumed, and then the other.

As will be seen, it consists essentially of a clamp holding two washers, each one encircling one of the carbon rods. The carbon rod is gripped by the tilting of the washer when the clamp is raised, and the clamp is so shaped (one of the jaws being wider and one washer having a larger hole than the other) that one washer is tilted more than the other. This causes one washer to grip its rod before the other. As the clamp is raised, the rod first gripped

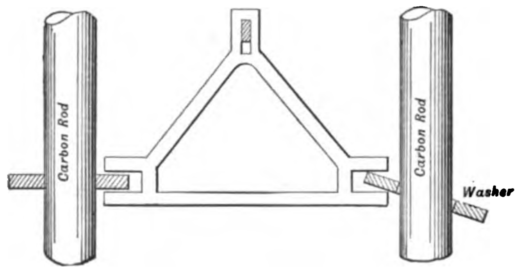


Fig. 277. Original Brush Clutch.

lifts its carbon from the negative, and the arc follows between the next carbon and its negative. In order to keep feeding the carbon last raised, and not the other one, a stop, or release, is so placed that on the descent of the clamp it will come in contact with the washer that has been most tilted, and release its grip on the rod before the other washer has struck the detent. When this carbon rod has descended its full length, the clamp in trying to feed falls still more, finally touching the release, allowing the second carbon rod to slip down and strike the arc. The extreme simplicity of this mechanism found immediate favor, and the short carbons that it was enabled to use materially lessened the cost of arc lighting. Practically the same device is applied at present in a modified form in all double-carbon lamps.

Carbon Feed. — Two methods are commonly employed to feed the carbons: In one, the clutch mechanism acts directly on the carbon, and this is termed direct or carbon feed. In the other form, the carbon is gripped by a clamp attached to a long rod, sometimes to a chain passing over a wheel, and the feeding is done by the action of a clutch gripping the rod or wheel. When the rod is used the lamp is known as a rod lamp, or in the case of a chain or band as a chain or band lamp.

Rod Feed. Taking up the rod feed first: The advantage it

offers is that the carbon is positively clamped in a holder making good contact between carbon and metal. The surface resistance of carbon is very high, causing a great tendency to arc unless the contacts are broad and substantial. The metallic rod usually has a smooth and polished surface on which the clutch grips, so that the action of the clutch is quite regular. If, instead of a tilted ring, a modified form of clutch is used, having a longer gripping surface, such as shown in Fig. 278, being the new Brush clutch, nicks or

Fig. 278. New Brush Clutch.

dirt on the carbon rod will not affect the evenness of the feed. The weight of the metallic rod makes its descent sure, and the current is fed to it easily by means of contact brushes or springs bearing on it. The disadvantage of the rod is that it requires to be polished or kept bright; that it is apt to warp by heat, or be bent by carelessness in handling; and that the length of the lamp is greatly increased since the carbon rod must be considerably longer than the carbon itself. The chain-and-wheel feed is a modified rod feed in which the clutch grips the wheel or chain instead of the carbon. This avoids the chance of bending the rod; and, as the wheel may be inclosed in the lamp, does away with the necessity of polishing the working surfaces that are tarnished by exposure to the atmosphere, as in the case of the rod. But the element of friction is introduced in all lamps having chain feed, which is apt to cause irregularity in a lamp after it has been in service some time and the parts have become oxidized.

Direct or Carbon Feed. Passing to lamps in which the clutch grips the carbon directly, it will be noticed that they have the advantage of minimum length, since the whole lamp need be but very little longer than the added lengths of the carbons used. The difficulty with these lamps is that the carbon has little weight, and will not descend with a positive action unless it is weighted by

some device at the top. This lengthens the lamp. Again, what is probably the greatest difficulty is the feeding of the current to the carbon. If this is accomplished by means of rings, or any sliding contact device, there will always be a tendency to arc if the parts become oxidized or covered with dust, since the contact between the carbon and the ring or brush cannot be very good without introducing too much friction. If a flexible cord is used to convey the current to the carbon, it requires a form of carbon holder which will take up considerable room, and needs a guide to direct the upper end of the carbon; furthermore a flexible cord is not a very reliable thing to employ, because continual bending of the wire and insulation will ultimately break the wire and fray the insulation.

Clutches. — A clutch is a device intended to move freely over a surface in one direction, and grip it when the movement is reversed. The usual function of a clutch in an arc lamp is to grip the carbon or rod so that it cannot slip until the clutch has been opened by descending far enough to touch a release. There are any number of different types of clutch, but as a rule the simplest are the best. Clutches are frequently constructed like an ice-tongs, which grip when the supporting weight is on them, but release as soon as pressed down. (See Fig. 295.) Any cam surface will act as a clutch when the pivot around which the cam moves is fixed, and the object is gripped between the edge of the cam and another fixed surface. There is a critical angle at which a clutch of this kind fails to work, varying according to the material of which the cam and the surface that it grips are made. A common value for this angle would be fifteen degrees above the horizontal. A good clutch should release the surface that it grips with the minimum effort by the release. The effect of a clutch sticking is to cause most of its weight to rest on the release, therefore varying the weight supported by the magnet coils, and causing irregular lengths of arc. If a clutch sticks badly the arc will lengthen until it goes out, in the case of constant potential lamps.

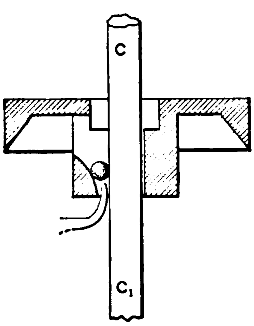


Fig. 279. Roller Clutch.

The roller clutch in Fig. 279 is self-evident in its manner of working. Such clutches as are not

specially shown will be found, in their many forms, on the cuts of lamp mechanism in this chapter. Other forms of mechanism that are not so much used in modern practice are the rack or escapement feed and the hot-wire mechanism.

The name of the former is sufficiently descriptive, and all lamps operating on this principle give the same trouble that a clock would if exposed to heat, dust, and atmospheric influences. When in good condition these clockwork lamps give fine results, but quickly get out of order.

The hot-wire lamp, shown in Fig. 280, is the other extreme, since it has practically no mechanism at all. One end of a wire made of an alloy with a high coefficient of expansion is fastened to the frame of the lamp. The other end of the wire, which usually passes several times up and down through the lamp, is fastened to a clutch, gripping the carbon. This clutch is held up by a spring working against the pull of the wire. For an inclosed arc lamp, the wire is in series with the arc. When the lamp is cold, the wire contracts, and draws the clutch and carbon down. When current is turned on, the wire heats rapidly, and expanding allows the spring to draw up the carbon, springing the arc. If the current increases, the wire expands further, allowing the spring to lengthen the arc and *vice versa*. Despite its apparent simplicity and positive action, there are several difficulties with this type of lamp. One is the lack of sensitiveness in the wire ; because small current variations have little effect upon the temperature, and a mechanism of this kind is slow to respond, compared with a solenoid or magnet. If the arc is accidentally extinguished, the length of time required to cool the wire so that the carbons touch again, is considerable. Such lamps are also affected by the surrounding temperature unless compensating wires are introduced, which destroy the simplicity. For alternating lamps the hot wire has the great advantage of being free from magnetic vibration. It is essentially a cheap and simple construction capable of greater development.

Fig. 280. Jones Hot-wire Lamp.

Inverted Arcs. — In order to obtain diffused illumination the arc is sometimes inverted (Fig. 281), so that most of the light is thrown on the ceiling to be reflected downward. In such cases it is usual to feed the negative carbon as it is then the upper one. It may be a trifle larger and the positive a little smaller than usual, since the rising heat of the arc adds to the rate of consumption of the negative instead of the positive. For a similar reason inverted arcs are almost a third shorter for a given voltage than ordinary arcs, and the efficiency is diminished. This results because it requires more energy to maintain the heat of the crater when it is underneath, which is equivalent to a less length for the same energy. Ordinary lamps are also used, with upturned reflectors underneath.

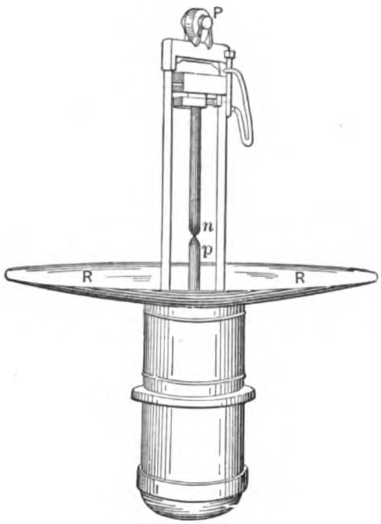


Fig. 281. Inverted Arc Lamp.

Lamp Mechanism. — The variations of open-arc mechanisms are almost endless, but with the previously explained principles any may be mastered with a little study.


Fig. 282. The Under Reflector.

In Fig. 283 we have the Thomson-Houston lamp mechanism, showing the electric circuits. It consists of a seesaw lever, *LL*, pivoted at *O*, and provided with a long tail, *T*, the motion of which is modified by an air dash-pot. Below is an electro-magnet, *M*, in the main circuit; and above is a second, *S*, which is connected as a shunt. The pole pieces are of conoidial shape, protruding through apertures in the armatures, *aa*, and *bb*, to give a longer range of pull. The lower and the upper arms of the clutch, marked *R* and *k*, close together when the tail, *T*, rises, gripping the carbon rod, *C*, and raising it. The current enters the lamp through an insulated terminal at + *P*, flows first around *M*, and then goes to the frame of the lamp.

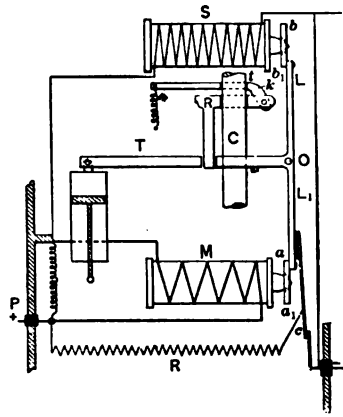


Fig. 283. Circuits of Thomson-Houston Lamp.

Thence it divides, the main current finding its way to the upper carbon-holder, and so through the arc to the lower carbon-holder, whence it returns (by a route not shown) to the insulated negative terminal, − *P*.

A smaller portion of the current flows up around the shunt electro-magnet to − *P*. The arc is struck by the preponderating main current in *M* attracting the lever end of the seesaw lever, and raising the clutch. The feeding is accomplished by the increased pull of the shunt magnet if the arc tends to become too long owing to the carbons burning away.

The resistance wire *R* from + *P* to *c* constitutes a cut-out circuit, which is brought into operation by the augumented current in *S* on any failure of the main current. The small coil connected across from + *P* to the lamp frame is a mere adjustment to regulate once for all the power of the series coil, *M*, relatively to the shunt coil, *S*.

Among the best-known open-arc lamps are the Brush (differential), Fig. 284; Thomson-Rice (shunt), Fig. 285; Adams-Bagnal (differential-focusing), Fig. 286; Bergmann (constant potential), and Westinghouse (alternating); and many other successful forms.

Mechanism of Inclosed Arc Lamps. In inclosed arc lamps a simpler mechanical construction has been reached, by reason of the greater length of arc permissible, and the introduction of independent units on constant potential mains. The general construction of d.c. and a.c. lamps is similar, the essential difference being the lamination of the magnetic parts of the a.c. lamps.

In a d.c. inclosed arc, the lower carbon is usually fixed in the bulb, and the upper carbon slides down upon it by gravity. To spring a quiet arc the upper carbon must be lifted about $\frac{3}{8}$ inch,

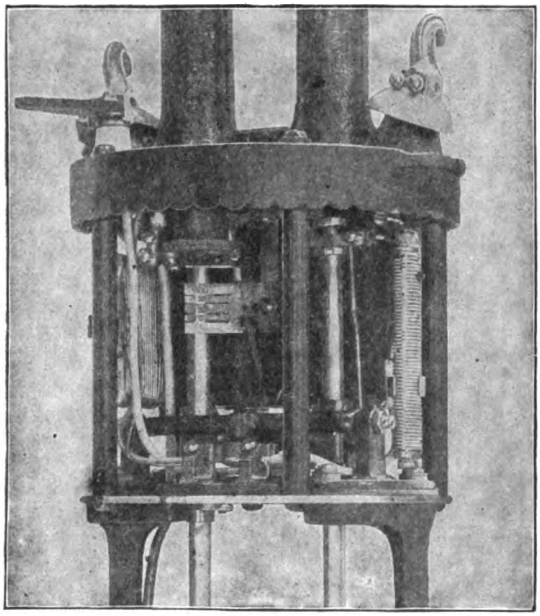


Fig. 284. Brush Lamp Mechanism.

and remain there, when the current is, say 5 amperes. The current should stay at 5 amperes whether the armature of the supporting magnet is near the upper or the lower part of its travel, and whether it carries the full weight of a new carbon or half the weight of one near the end of its run. The carbon must feed down a little each time the armature drops to the feeding-point, without greatly varying the current. In any case the current must be fed to the moving carbon by some positive device, as the contact resistance of carbon is high and variable.

Effect of Weight of Moving Parts. The weight of a carbon 12 inches long and ½ inch in diameter is 2 ounces. After a run about 6 inches will be left in the holder. Thus the weight of the moving parts has decreased by about one ounce. If originally the total weight of carbon, clutch, armature, etc., was 5 ounces, and it required a current of 5 amperes to hold them in balance, then 4 amperes will balance the weight at the end of the run, and the

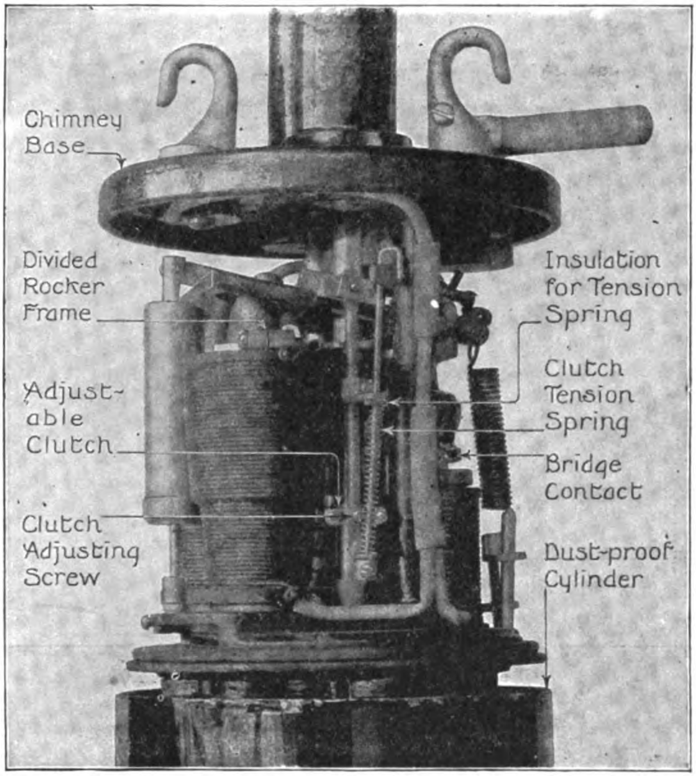


Fig. 285. Thomson-Rice Lamp Mechanism.

lamp gives less light. Unfortunately to this is added the effect of the dust which has collected in the bulb during the run. It is, therefore, very desirable to keep the current as nearly the same as possible, but this necessitates heavy moving parts like a carbon rod or weighted carbon-holder. With a total weight of 10 to 20 ounces, the decrease of current with carbon consumption is usually too small to be objectionable. Having settled on the allowable

current variation from beginning to end of run, the next consideration is the current variation caused by the position of the armature.

Effect of Position of Armature. The magnet or solenoid with 5 amperes of current should exactly balance the weight of the

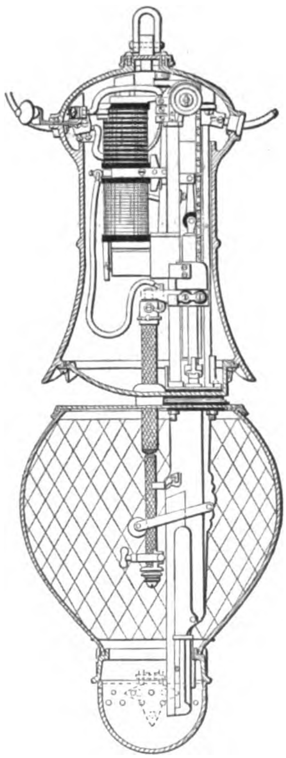


Fig. 286. Adams-Bagnall Lamp.

Fig. 287. Carbon-Feed, Constant Potential, Direct Current Lamp.

moving parts anywhere within their limits of travel, usually $\frac{3}{8}$ to $\frac{5}{8}$ of an inch. The best procedure to ascertain the accuracy of a mechanism is to disconnect the arc gap, and substitute for it an adjustable resistance. Adjusting the current to 5 amperes, the armature will usually be found to travel upward when near the

solenoid, but fall when some distance down. This would be a departure from perfect design, and should be avoided as much as possible. Magnetic parts can be constructed to balance at any part of a $\frac{5}{8}''$ travel within one per cent of the normal current. It may occur that with an armature in the upper position only $4\frac{1}{4}$ amperes will be required to hold it there, while at the lower limit of travel $5\frac{1}{2}$ may be necessary. Such a lamp would have a variation of at least $1\frac{1}{4}$ amperes, depending on the position of its armature. The latter varies anywhere from top to bottom, according to how delicately the clutch feeds the carbons and according to the voltage. If the clutch allows only a very small length of carbon to slip down when it feeds, the armature will tend always to hang near the position of clutch release unless the line voltage rises accidentally.

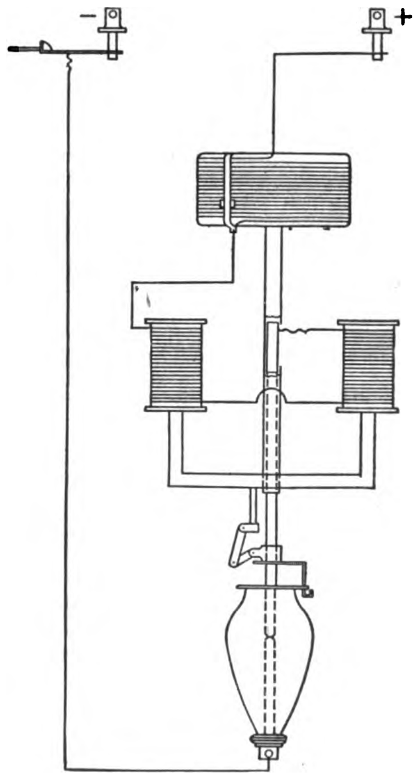


Fig. 288. Electrical Circuits in Fig. 287.

Effect of Levers and Complications. Some lamps contain combinations of levers or link motion by which the balance of the moving parts is affected. For instance, the carbon and holder may be partially counterbalanced by weights, or the clutch or solenoid may act through a lever or at an angle. In such cases it is important to see that the introduction of the levers, etc., does not vary the weight upon the solenoid by reason of the leverage changing with the position of the armature. It is also necessary that the net weight, after deducting for any counter-balancing, is large compared to the weight of the carbon alone.

Effect of Friction. In all lamps the working parts and carbons move with more or less friction in the guides, dashpots, gas-cap,

etc. This introduces a variation in current equal to double the current equivalent of the friction. This may be detected as follows: stroke the moving parts gently in a downward direction, and release them gradually. They will rise until the solenoid has overcome the weight plus the friction; then note the current, which may be $5\frac{1}{4}$ amperes. In the same manner raise the moving parts slightly, and allow them to descend gently, when the solenoid overcomes the weight minus the friction, and the current will be, say $4\frac{3}{4}$ amperes. This would be a frictional variation of one-half ampere.

Causes of Variation of Arc Voltage. It is, of course, understood that variations of current produce corresponding changes of voltage at the arc, where the arc is in series with a resistance as it is in constant potential direct current work. A further change arises from the increase of the resistances in series with the arc due to heat. A resistance drop of perhaps one volt occurs in the average carbon, possibly two volts in the magnet winding, but the larger part in the series resistance. When the lamp has become thoroughly heated, the drop may have increased nearly one volt in the magnet, and several volts in the resistance, unless it has been made of material having a low temperature coefficient. If the total increase in drop amounts to more than three or four volts it becomes quite noticeable in the arc. We must also take into consideration the fluctuation of line voltage superimposed on the resistance variation, which may be anything from two to twelve volts or more. If the lamp is perfectly adjusted to maintain constant current, the drop in the resistance being the same, the arc voltage varies exactly with the line voltage; if out of adjustment, the arc voltage is still more unsteady.

Cumulative Effect of Disturbances. The several disturbing factors are sometimes cumulative, and tests on the same lamp at different hours of the day, with varying positions of the armature, different periods of the run, etc., often show an astonishing variation.

For example, take the following data for a lamp, not worse than many found in everyday practice: —

Current balancing a 12″ carbon in a given position of armature	5^1 amp.
" " 6″ " " same " " "	5 amp.
" with a given carbon when mechanism is rising	$5\frac{1}{4}$ amp.

Current with a given carbon when mechanism is falling	$4\frac{3}{4}$ amp.
" balancing a given carbon (armature up)	5 amp.
" " " " (" down)	$5\frac{1}{4}$ amp.
Resistance (magnet and resistance wire) cold	6 ohms.
" hot	7 ohms.

Mains at different hours vary from 117 to 112 volts.

With the lamp hot after the first few hours of its run, armature low, and being raised against friction of carbon in gas-cap, etc., the current and voltage will be:—

Current = $5\frac{1}{4}$ amp. due to long carbon + $\frac{1}{2}$ amp. due to position of armature + $\frac{1}{4}$ ampere due to friction	$6\frac{1}{4}$ amperes
Drop in resistance hot ($7 \times 6\frac{1}{4}$)	43.75 volts
With mains at 112 volts, we have arc voltage (112 — 43.75)	68.25 volts

with $6\frac{1}{4}$ amperes of current.

With lamp cold, started after 140 hours previous burning, armature high and descending, the other extreme condition will be:—

Current = 5 amp. due to short carbon — $\frac{1}{4}$ due to friction	$4\frac{3}{4}$ amperes
Resistance (magnets and resistance wire) cold	6 ohms
Drop in resistance ($6 \times 4\frac{3}{4}$)	$28\frac{1}{2}$ volts
With mains at 117 volts arc voltage is ($117 - 28\frac{1}{2}$)	$88\frac{1}{2}$ volts

with $4\frac{3}{4}$ amperes of current.

This lamp might vary from $88\frac{1}{2}$ volts at $4\frac{3}{4}$ amperes to $68\frac{1}{4}$ volts at 6 amperes, without considering the variation introduced by the clutch release supporting more or less of the weight of the moving parts at the feeding-point. When it is remembered that the same lamps with the same adjustment are used in different parts of a building with an isolated plant, or in various parts of central-station territory where the extremes of voltages at different hours are much larger than those given above, and the lamps themselves worse, it is not surprising that some lamps are unsteady, give irregular life, and show blackened bulbs. High arc voltage produces short carbon life and clean bulbs, low voltage vice versa. High current tends to burn the dust into the bulb, deposits unconsumed carbon on it, and may even soften it. Poor inclosure at gas-cap edges, center, or at the base of the bulb, reduces the life. Too perfect inclosure results in blackened bulbs, due to unconsumed carbon. Gas-caps often warp after being greatly heated, asbestos washers for bulbs often chip, dashpots stick, etc., so that when difficulty is experienced in the operation of a lamp it must be

patiently ferreted out, whether due to the lamp construction, the carelessness of the trimmer, or the fluctuations of the circuit. The curves below illustrate the result of weeding out difficulties in lamp mechanism one by one. Fig. 289 shows the lamp current, and Fig. 290 the line voltage of a poor lamp under unfavorable conditions. Fig. 291 is current for the same lamp, its faults corrected on the same circuit, the voltage card being the same as

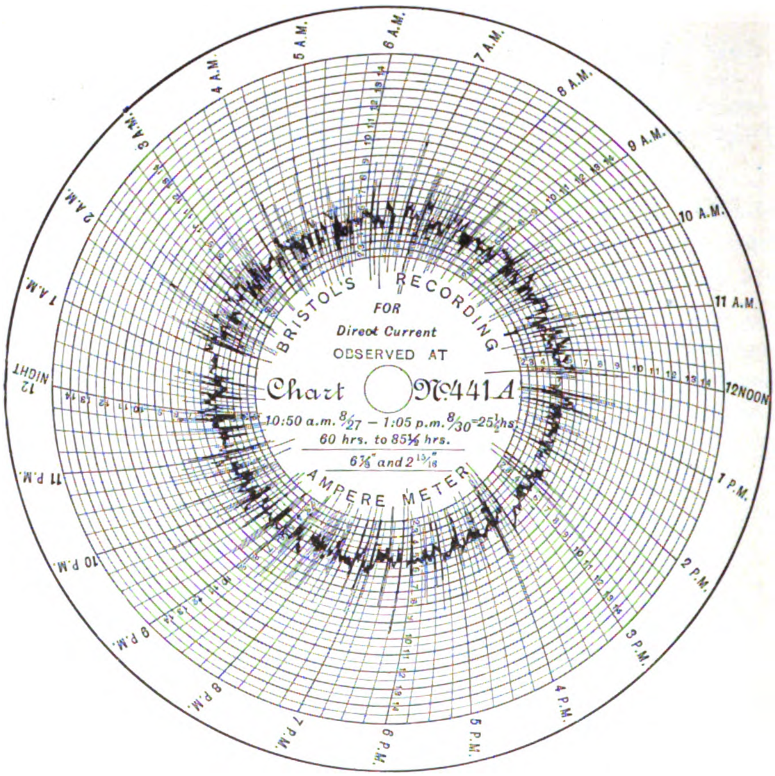


Fig. 289. Current Variations in Badly Adjusted Lamp.

before (Fig. 290). As modified, it shows constant current under violently fluctuating line voltage.

Function of Dash-pots. Air dash-pots are used in most lamps to overcome the tendency of the moving parts to overshoot on account of their inertia. When constructed so as not to become corroded, clogged with dust, nor warped by heat, they offer very little resistance to slow motion, but effectually check the too rapid or excessive motion due to inertia.

Usual Current and Voltage. In inclosed arc lamps for constant potential direct current circuits, the arc is usually run with 5 amperes, at about 79 volts. The voltage may be as high as 95 volts if the mechanism is sufficiently sensitive. It is usual to interpose resistance alone between the mains and the arc, but it is claimed that a considerable amount of self-induction can be used to replace part of the resistance. As a rule, the higher

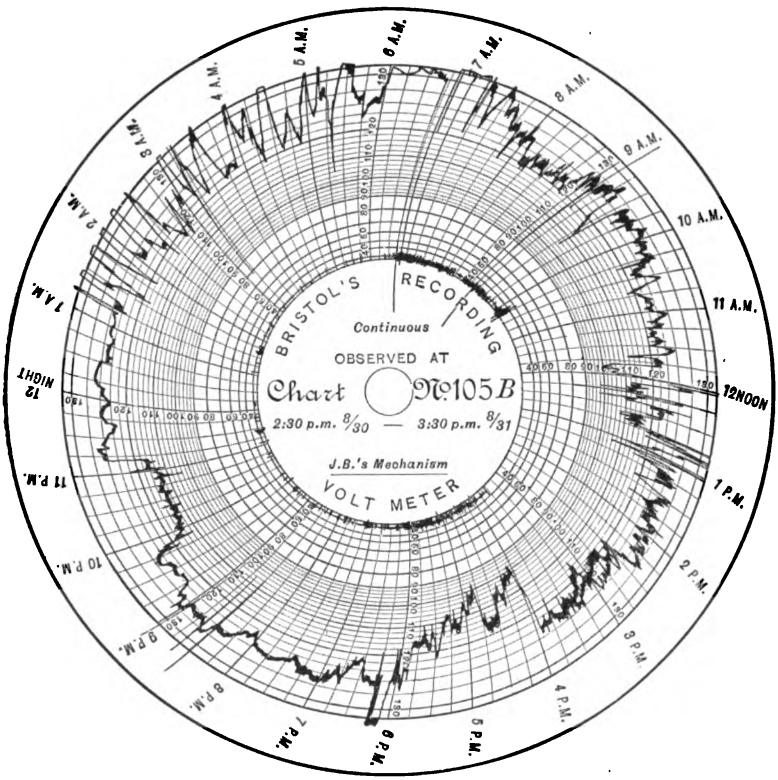


Fig. 290. Variable Voltage of Supply Circuit.

the line voltage, the higher the permissible voltage at the arc, but only within narrow limits. High-voltage arcs tend to waver and cut out. Roughly speaking, the most economical line voltage for d. c. constant potential inclosed lamps is about 105 volts.

Constant Potential Alternating Inclosed Arcs. For constant potential alternating circuits the inclosed arc has come into extensive use, with a voltage of 70 to 73 at the arc and 6 amperes.

Such lamps (Fig. 292), are similar to direct current lamps except for the lamination of the magnetic parts, the use of an adjustable reactance coil in place of a resistance, and the cushioning or spring suspension of the parts that vibrate and tend to produce humming. The reactance coil is usually adjustable to compensate for secondary voltages between 100 and 120, and cycles from 60 to 140. Since the lower carbon is consumed nearly as fast as the

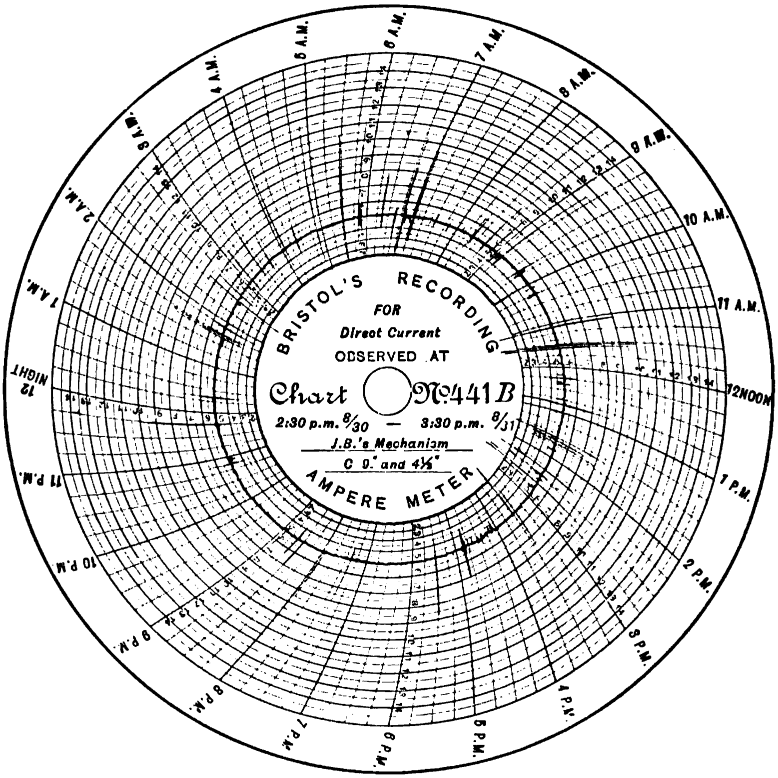


Fig. 291. Current in Readjusted Lamp.

upper one, a. c., inclosed arcs are provided with long bulbs to permit of a long lower carbon being used. As already mentioned, one cored and one solid carbon give the highest voltage arc that will be stable. The upper is usually $9\frac{1}{2}$ inches long for a six-inch lower, this difference being necessary because the upper carbon is consumed somewhat faster, and because it must project from its holder down through the gas-cap far enough into the bulb so

that the arc will not be sufficiently near the gas-cap to injure it. The life being limited by the length of the lower carbon, which, in turn, is limited by the length of the bulb, these lamps burn only 80 to 100 hours. Of 625 apparent watts a good lamp con-

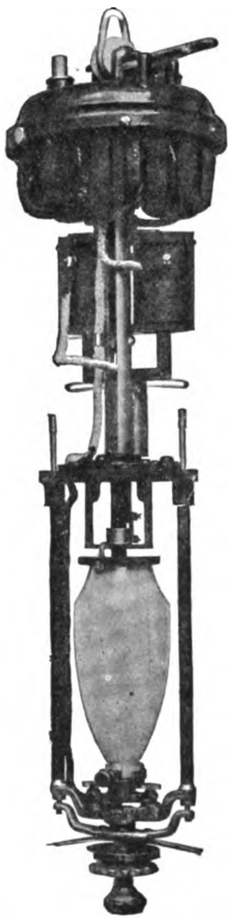


Fig. 292. Carbon-Feed, Constant Potential, Alternating Current Lamp.

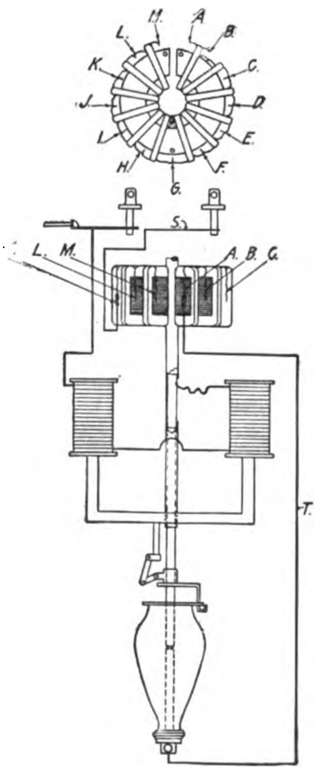


Fig. 293. Electrical Circuits in Fig. 292.

Fig. 294. Carbon-Feed, Constant Direct Current, Series Lamp.

sumes only 430 to 450 true watts, of which 35 are lost in the reactance coil.

Direct Current Inclosed Arcs for Series Circuits. Inclosed arcs for d. c. series circuits are either shunt or differential the same as open arcs. (Figs. 294, and 295.) They are used on cir-

cuits of 5 to 6.8 amperes, with 68 to 75 volts at the arc, and burn from 100 to 140 hours. The differential lamps require some temperature correction to compensate for the decrease of current in the shunt winding of the magnet, as its resistance rises with heat. They may also be readjusted to circuits of various current

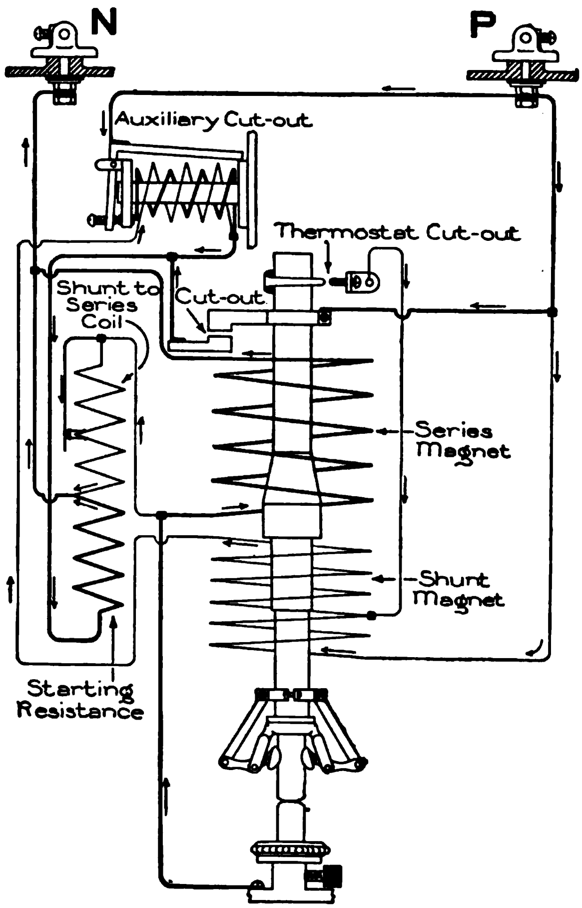


Fig. 295. Electrical Circuits in Fig. 294.

strengths by shunting more or less current through a small auxiliary resistance, and like open arcs are usually provided with a resistance in series with the automatic cut-out. When the cut-out operates, it short circuits the lamp terminals through this resistance, thus maintaining sufficient difference of potential

across the magnets to enable the lamp to start up again if nothing is wrong with it.

Inclosed Arcs for Series Alternating Circuits. Many alternating stations have street-lighting circuits, most of which have been operated by series direct current machines and lamps, thus employing two kinds of generating machinery. Series circuits are particularly adapted to widely scattered lamps outside of the regular lighting service, on account of the low cost of the single-wire series line. Furthermore, it is usually desirable to have the street lamps on one or more independent circuits, so that they may be lighted or extinguished from the station. By using the series alternating arc system this can be effected without separate machinery. It consists of the lamp circuit, and a device connected to the regular constant potential alternating mains, which will maintain a constant alternating current in the independent lines.

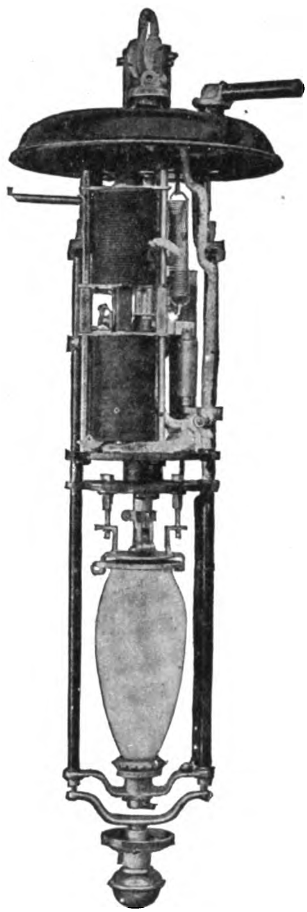


Fig. 296. Carbon-Feed, Constant Alternating Current, Series Lamp.

One method is to use a transformer already described (p. 171) having excessive magnetic leakage, whereby the secondary is made to deliver constant current. Another device is an automatically varying reactance coil connected directly to the primary mains, which adjusts the amount of self-induction in accordance with the instantaneous impedance of the series circuit in such degree as to maintain constant current. Such devices are capable of keeping the current at 6 amperes, within one-tenth ampere either way. Of the two, the variable self-induction has the advantage of low first cost and repair, small space, and greater simplicity. When of the proper size for the number of lamps to be governed, its power factor and efficiency are higher than those

of the transformer, and it permits of simple adjustment to greater current strength, if more light is demanded by the municipal authorities. It has the disadvantage of connecting the primary mains directly to an external circuit. Fig. 135 shows the internal arrangements of a 100-light General Electric series transformer which was fully described on page 172, and Fig. 298 the appearance of a Manhattan regulator.

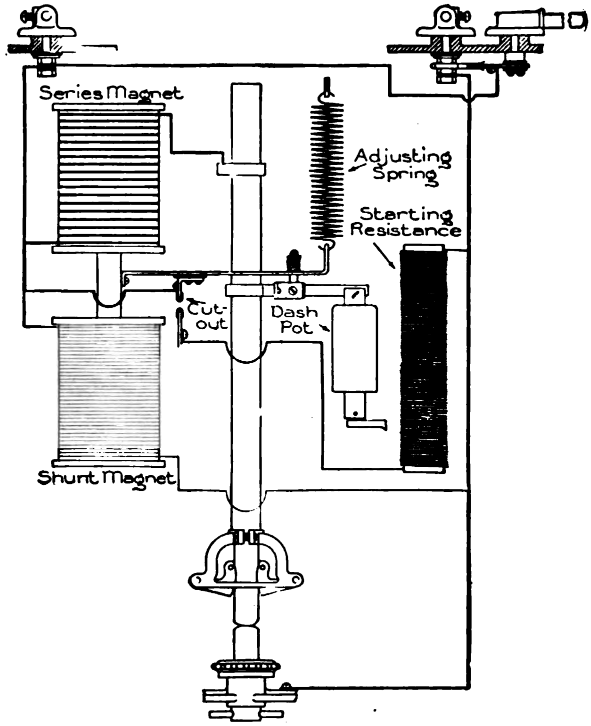


Fig. 297. Electrical Circuits in Fig. 296.

In the regulator a reactance coil in series with the lamps is balanced against a weight in such a manner that it incloses more or less of the central leg of a W-shaped core. When the current rises, the coil is magnetically drawn in by the core, thus increasing the self-induction, and reducing the current to normal.

Fig. 299 shows the mechanism of a Manhattan series alternating lamp, which is of the shunt type. The cut-out includes a small magnet in its circuit, which holds the cut-out contact closed when it has once operated after the carbons are consumed.

The number of series a.c. lamps permissible on a circuit with a regulator is approximately the line voltage divided by 80. More than this tends to cause simultaneous jumping of all the lamps. In either system the watt loss in the regulating device is only the iron loss and the small resistance loss, but the regulator has somewhat less than the transformer. The shunt lamp has the same voltage at the arc as at the lamp terminals, while the differential

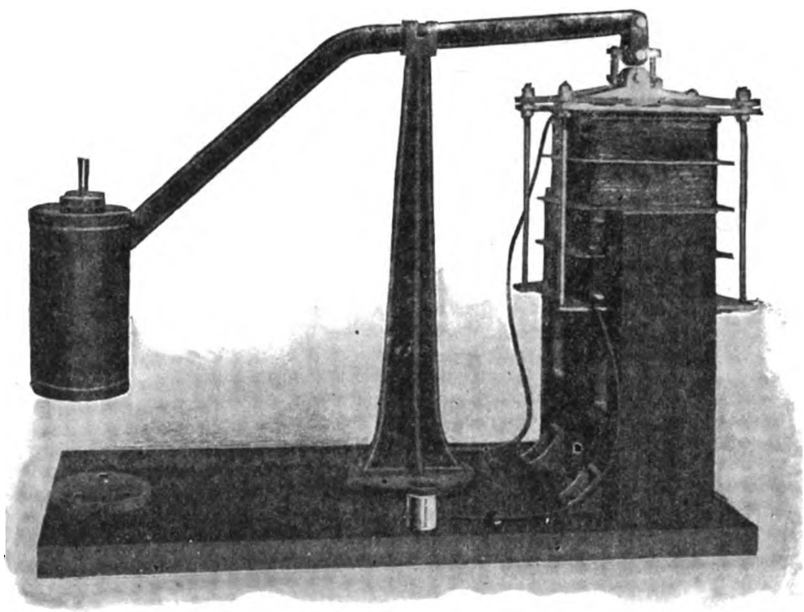


Fig. 298. Constant Alternating Current Regulator.

lamp has 4 or 5 volts less. The arc, in either case, runs at about 70 volts with 6½ amperes. The power factor of an entire system of regulator and lamps may be as high as 88 per cent.

Light Efficiency. The luminous efficiency of the series alternating lamp is considerably lower than that of a corresponding direct current series open arc, and half of the light would be directed upward were it not for the reflector, which may send downward again nearly 90 per cent of the up-going rays. Despite its lower efficiency, it gives satisfactory and high apparent illumination, since the pupil of the eye is not contracted by the lower light intensity from the large surface of bulb and reflector,

nearly as much as from the small and intense crater of the open arc. The pavement below the lamp is more free from the violently contrasting bands of light and shade, characteristic of the open arc, thus producing the appearance of more uniform brightness. For these reasons, largely, municipal authorities often prefer the series alternating lamp with its lower efficiency to open direct current lamps consuming the same energy.

Fig. 299. Series Alternating Current Lamp.

Fig. 300. Mounting of Hood upon Pole.

Street Arc Lamps must have additional features, such as hoods, pulleys, mast arms, suspension hooks.

Hoods should be so arranged and set on the pole tops as to cast the minimum shadow. (See Fig. 300.)

Where a lamp is suspended it is well to have some arrangement which cuts out the lamp when lowered to trim.

That the lamp is held independent of lowering rope, and hence will not fall if rope should be broken, is a valuable feature of any arc suspension. (See Fig. 301.) These pulley suspensions hold the lamp when raised, and release it when about to be lowered.

On raising the lamp a knob is engaged by ridges on the sides of the pulley, and takes all strain off the rope. A pull at the rope guides the knob out, so that the lamp can readily be lowered. Mast arm and pole arrangement is shown in Fig 302. A suspension canopy is shown in Fig. 303, and side bracket suspension in Fig. 304. An arc light cut-out switch is represented in Fig. 305.

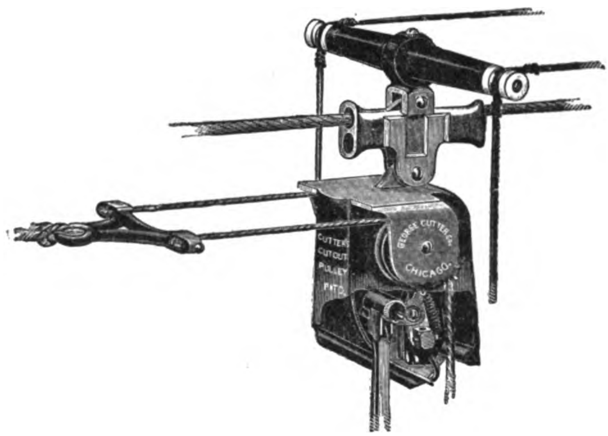


Fig. 301. Cut-out Pulley.

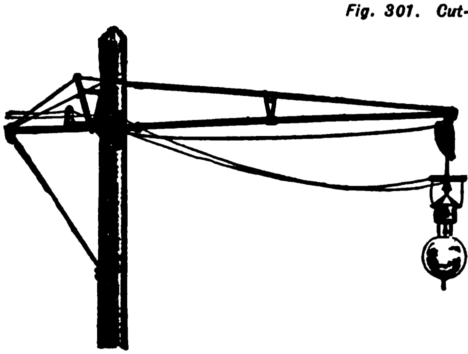


Fig. 302.

Fig. 303. Hood for Suspension.

Projection Apparatus. — *Special forms* of arc lamps are used in electric projection lanterns, photo-engravers' lamps, stage projectors, locomotive headlights, etc. The life of the carbons in such apparatus is of minor importance, and they are usually of the open-arc type. The carbons are generally inclined away from the object so that the maximum rays at an angle of about 45° (Fig. 307) from the axis of the positive carbon will be directed nearly horizontally at the point to be illuminated. Besides being tilted, the upper

carbon is often set back somewhat out of line with the negative, which brings the crater at an angle without requiring the tilting of the carbons, as represented in Fig. 306. These lamps are

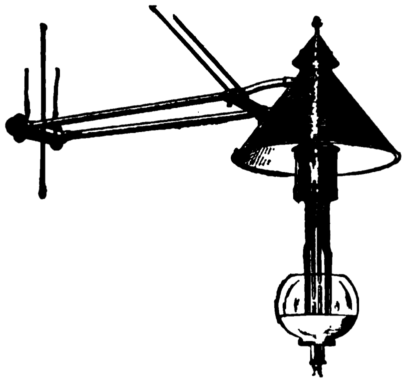


Fig. 304. Bracket Suspension.

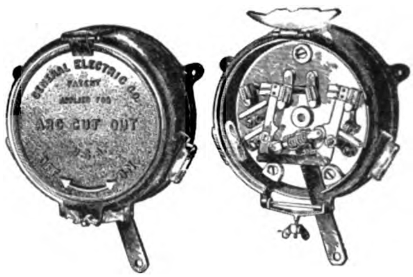
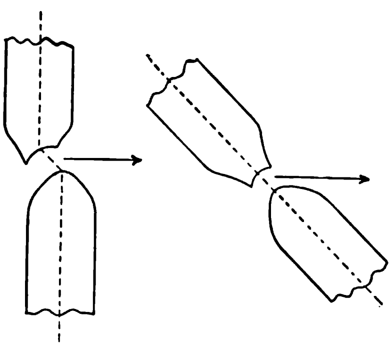


Fig. 305. Series Cut-out Switch.



Figs. 306 and 307. Position of Carbons in Projector Lamps.

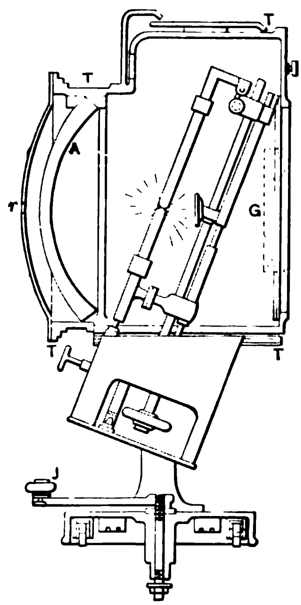


Fig. 308. Search Lamp with Mangin Mirror.

frequently made with hand or clock work feed, partly because of the difficulty of feeding inclined carbons by gravity, and because they are under the care of an operator. A reflector with a polished or dead-white surface is placed *behind* the arc.

In search-light projectors, on the contrary, the arc is directed *toward* the reflector and away from the object to be illuminated. This is done in order that all the emerging rays shall be parallel, in which condition their intensity is theoretically the same at any

distance but practically not, owing to unavoidable dispersion due to the size of the light-emitting surface, aberration in the reflector, and the refraction and absorption of the atmosphere. With the crater turned toward the front of the search-light all of its rays that did not strike the reflector would be divergent instead of parallel. In search-lights the carbons may be either inclined or horizontal, in which latter case the positive is in front. The

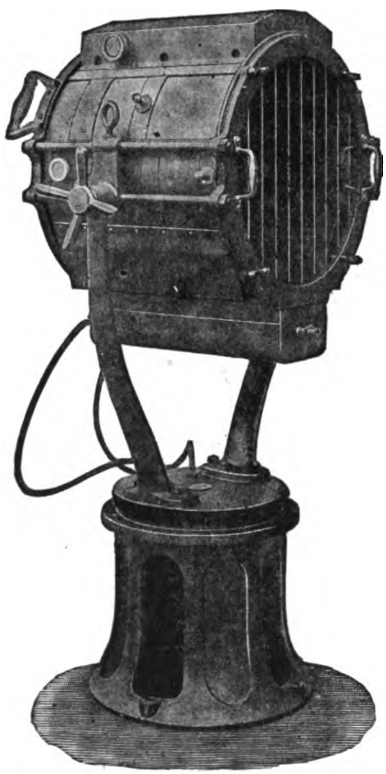


Fig. 309. Search Lamp.

carbons may both be solid if of high-grade soft carbon, but frequently the positive is cored. To keep the arc stationary the carbons must either be fed at different rates of speed, or may be suitably proportioned, the positive being cored and larger in diameter than the negative. Any variation of the arc from the focal position may be corrected by hand, using the colored-glass windows provided for that purpose. The feeding mechanism is

usually motor-actuated so as to be positive. At the sides the light is surrounded by a cylindrical casing, supporting at the rear a reflector far enough away not to be damaged by the heat of the arc. These reflectors, in cheap search-lights for mining and contractor's work, are sometimes made of silvered copper, but are preferably of glass. The latter are made in two styles, aplanatic and parabolic. The aplanatic or Mangin mirror has two spherical but not concentric surfaces, as shown in Fig. 308. Owing to its unequal thick-

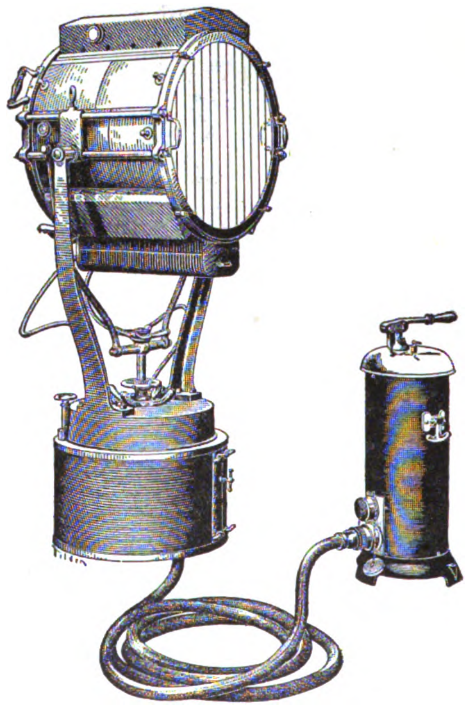


Fig. 310. Search Lamp.

ness it is somewhat more liable to crack than the parabolic. The latter is a truly parabolic piece of silvered glass about ¼ inch to ½ inch thick throughout. The front of the search-light is closed by plate-glass strips (Fig. 309) instead of one piece, to avoid breakage by heat, and to allow easy renewal of a broken section. In case the light is intended to cover a greater area, that is to diverge, a diverging front of lens strips, usually for a 20° divergence, may be swung into place instead of the plane strips, although

the same effect may be produced by moving the arc out of its correct position. Average values for the current in search-light projectors of various sizes are about:—

45	amperes	for	an	18-inch	light	
80	"	"	a	24	"	"
125	"	"	"	30	"	"
150	"	"	"	36	"	"
200	"	"	"	48	"	"

The commercial ratings of candle-power of search-lights are misleading. The average light intensity of the beam is multiplied by

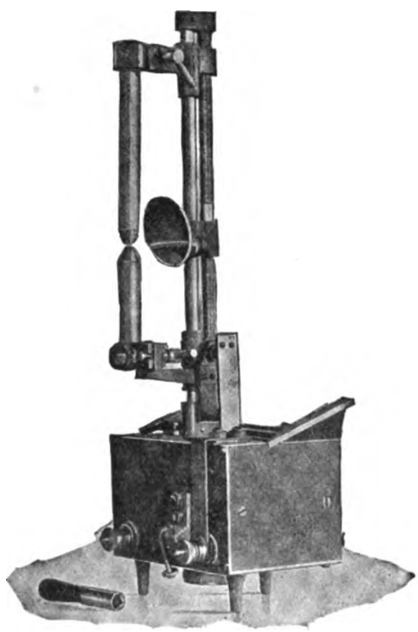


Fig. 311. Projection Lantern.

its area to get the total flux. The rated candle-power is then obtained by dividing this figure by the area of the crater, which gives relatively but absurdly high values to the candle-power. Thus, supposing that an arc with a mean hemispherical candle-power of 10,000 were combined with a Mangin reflector two feet distant, the average illumination on the mirror would be $\frac{10000}{(2)^2} = 2500$ candle-feet; and if we neglect small losses, this will

be the intensity of the beam. To multiply this value by the ratio $\frac{\text{area of beam}}{\text{area of crater}}$, gives for any possible values of the numerator and denominator a figure much greater than 10,000, the true candle-power of the arc. A more rational method would be the product of the light intensity of the beam in candle-feet, by its area.

The movements of the beam of light are produced independently of the arc mechanism, by hand or by distant motor control. In the latter instance the projector may be provided with a vertical wheel and chain actuated by a motor, which turns the barrel around a horizontal axis, as well as with a motor-driven revolving base, to swing the whole lamp in either direction. These motors may be operated by a distant controller, and the lamp suitably fitted with a two-joint receptable for the lighting cables and usually a five-point socket for the motor cables

CHAPTER XVI.

INTERIOR WIRING.

The laying of electrical wires does not appear to be as important from the engineering point of view as the construction of overhead and underground conductors; nevertheless, an additional and most important consideration is involved, this being the fire hazard. When electric lighting was first introduced this difficulty was so great, being naturally magnified by prejudice against the new method of illumination, that insurance and municipal fire department authorities were often strongly opposed to the introduction of electrical conductors into buildings. But improvements in methods of construction have gradually reduced the risk, until now insurance companies and fire departments consider electric lighting less dangerous than any other form of artificial illumination. This is undoubtedly a fact; but electrical wires are still the cause of many fires, the consequences of which are often very serious. Hence, it behooves those who are responsible for the installation of electrical apparatus and conductors inside of buildings, to exercise the greatest possible care. This is the more necessary, in view of the conditions under which electric light wiring must be installed to meet the varied requirements. In a large class of installations no small amount of judgment, ability, and ingenuity is often required to overcome the difficulties met with, to adapt the material at hand to the purposes, or to devise new methods to secure unusual results. Slaughter houses, dye houses, chemical works, bleacheries, and breweries offer many peculiar difficulties to proper wiring.

Before the actual interior wiring can be of use it must be connected with the service wires, and this necessitates in most cases that at some point the wires enter the building. In order that the moisture may not travel along the wires from outside to the interior installation, there is at the service entrance a drip loop outside; and the hole through which the conductors must pass is

bushed with a drip tube, which must slant up towards the inside. (See Fig. 312.) The wire entering these tubes should have solid rubber insulation, at least $\frac{3}{64}$ of an inch thick, and covered with a substantial braid. The space between the wires as they enter the building should be at least one foot, and arranged so that no cross connection can be made by water. The wires should never come in contact with anything but their insulators. Running them along the face of the building should be avoided, and they must be fastened to the wall near the entrance tubes by insulators mounted on special brackets having two coats of waterproof paint to prevent the absorption of moisture.

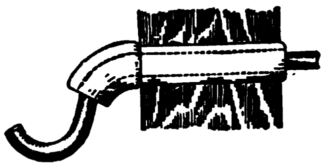


Fig. 312. Drip Tube and Loop.

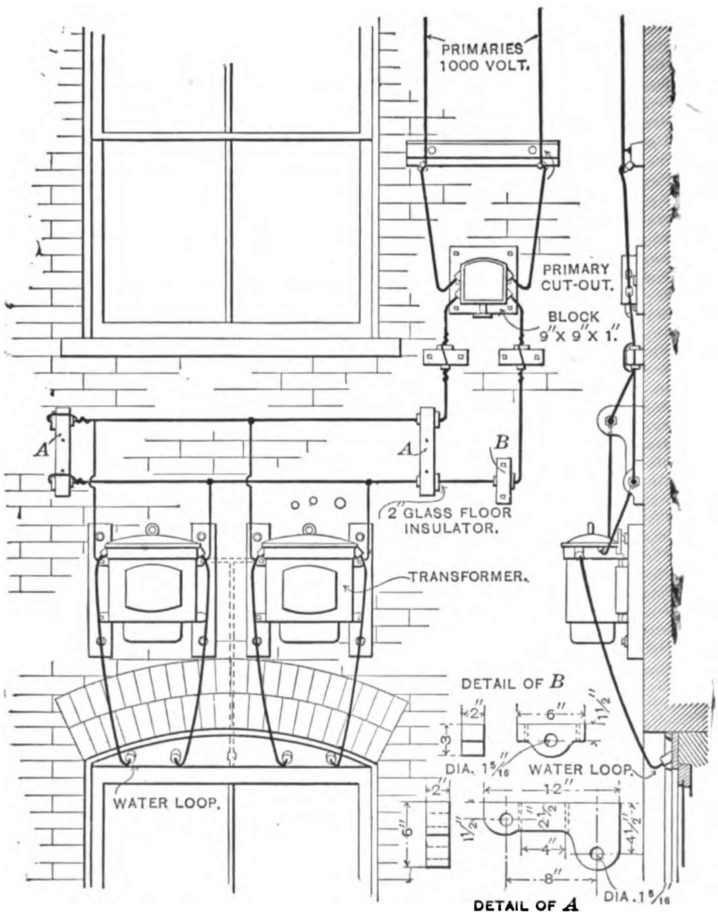
Automatic cut-outs such as circuit breakers or fuses should be placed on each of all service wires as near as possible to the point where they enter the building, on inside of the walls, and arranged to cut off the entire current from the building. The wires then run to the service switch, which should be capable of opening the circuit when carrying the entire current of the building. This is a knife switch, and should be installed so that the handle will be up when the circuit is closed, so that gravity will tend to open the switch, rather than accidentally to close it.

With alternating systems the best place for the transformer is on the pole away from the building. The transformer, when placed on the outside wall of the building, must be hung on well-insulated supports, the construction being as shown in Fig. 313. Where it is impossible to exclude it from the building, the proper place is a vault or room with brick walls containing nothing else but transformers. As a last resort it may be put in a part of the cellar where it is well ventilated and dry, being carefully insulated from the walls and the ground.

The next piece of apparatus in the building is the switch board or in small installations the distributing panel board. This will carry the meters, the knife switches and the fuses for the feeders. If electric power is to be used besides the lighting the separation of the two kinds of circuits should be made at this point.

The principal methods which have been, or now are, used to carry the wires from the entrance devices to the lamps are as follows:

(1) Wires inclosed in molding.
(2) Wires carried by wooden cleats. (Obsolete.)
(3) Wires carried by porcelain cleats or knobs in open work.
(4) Wires carried by porcelain knobs and tubes concealed.
(5) Wires concealed in plaster. (Obsolete.)
(6) Wires concealed in tubes, interior conduits.
(7) Wires laid on some cornice, wainscoting, or other architectural feature adapted to the purpose.
(8) Fished wires. (Not desirable.)



From *Standard Wiring* by H. C. Cushing, Jr.

CONSTRUCTION WORK
INSTALLING TRANSFORMERS

Fig. 313.

Three of these — i.e., the second, fifth, and eighth — are no longer considered good practice, in fact they are forbidden by the National Electric Code. In order, however, to fully appreciate the difficulties in this important branch of electrical engineering, it will be well to consider all of the above methods in the order given.

Wooden Molding. — The advantages of this construction are simplicity, cheapness, and accessibility. It is particularly applicable to buildings in which no provision has previously been made for electrical conductors, the wires being laid after the building is completed. At first this was the general condition, and a very large proportion of the wiring laid during the early history of electric lighting was installed in this way. At present the use of electric light is decided upon, or at least contemplated, before the

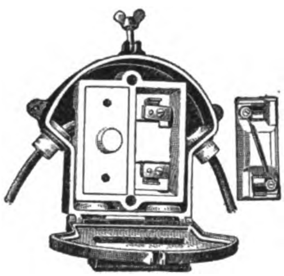


Fig. 314. Primary Cut-out.

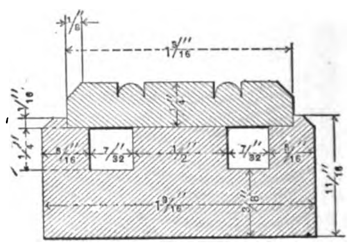


Fig. 315. Two-wire Molding.

building is erected, and the plans provide specially for it. In such cases, particularly where expense is not a prime consideration, the use of the so-called "interior conduit," laid in the walls, is the standard practice for low tension (below 450 volts circuit). For high-tension wires, the only approved plan is to carry them upon porcelain knobs or cleats. These two methods will be considered later, in their proper order.

Wooden molding usually has the cross-section represented in Fig. 315, consisting of a strip or "backing," in which are cut grooves corresponding to the number of wires to be laid, only one conductor being placed in each groove. The backing is fastened to the wall by thin wire nails or brads, being made continuous as far as possible. Angles and branches are formed by fitting pieces together, as indicated in Fig. 317. The wires are then laid in the grooves, being also preferably continuous, although joints are

allowed, provided they are securely made mechanically by splicing and soldering, and provided the insulation is made equal to that of the rest of the wire by careful wrapping of tape. The capping is then put in place, and fastened by small tacks or brads. Molding has been used in which the grooves were formed in the capping without any backing. This, however, is bad practice, and should not be adopted even where the wires are laid against a wooden wall or ceiling.

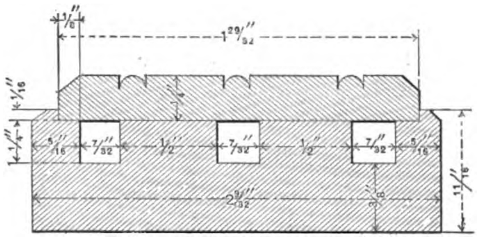


Fig. 316. Three-wire Molding.

The chief disadvantages of wooden molding are the facts that it is not sufficiently impervious to moisture, is liable to be crushed or punctured mechanically, and is combustible. These difficulties are overcome as far as possible by coating the molding, both inside and out, with water-proof paint, or by impregnating it with moisture repellent. It is also recommended that only hard-wood molding be used. But soft-wood molding is often laid because it follows the wall line better. In the standard forms, the backing is at least three-eighths of an inch thick under the grooves, and one-half an inch between them. The capping should set in one-sixteenth of an inch, or more, into the backing, and should lap over the grooves not less than one-eighth inch on each side. These minimum dimensions are represented in Figs. 315 and 316, but much larger sizes of molding are used for heavier wires.

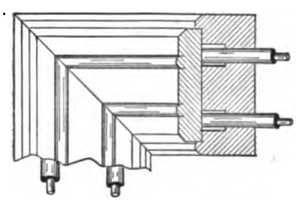


Fig. 317. Right Angle Joint in molding.

Rats gnawing through a molding may destroy the insulation of the wire, and bring the copper in contact with the wood.

Wires for use in molding must have rubber insulation, at least $\frac{3}{64}$ of an inch thick; and as the size of the wire increases from No. 14 to No. 0000 the thickness of the rubber changes to $\frac{5}{64}$ inch.

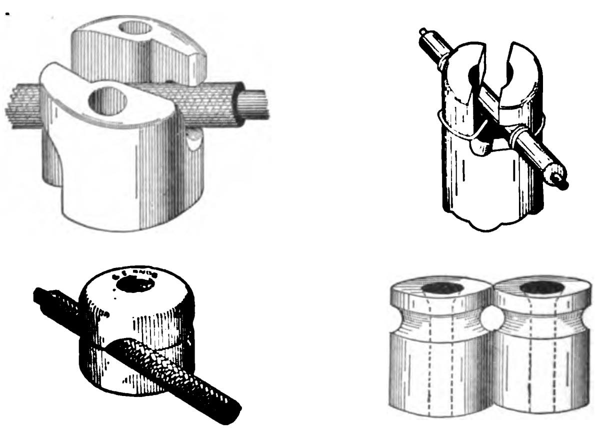
In molding where one of the wires must cross over, it is

brought out through the capping and across it, so that a certain thickness of wood is between the two conductors.

Wooden Cleats. — These may be looked upon as a discontinuous molding. In fact, their cross-section is practically the same. Their use is rarely to be tolerated at present, cheapness being their only recommendation. Experience has shown that it is a great mistake to attempt extreme economy in the laying of electrical conductors. The serious difficulties which arise in the shape of damage by fire and interruption of service are far more expensive in the long run than a considerable increase in first cost.

Wooden cleats have all the disadvantages stated for wooden molding, and are open to two additional objections. One of these is the fact that the wires are left exposed for a large portion of their length, and are therefore liable to be injured or to form a short circuit or ground connection by coming in contact with each other or with some pipe, nail, or other conducting body. Wooden cleats are also likely to have small splinters projecting from them which cut through the insulation of the wires, and have been found to be a source of much trouble.

Porcelain Knobs or Cleats. — In open work various forms of these devices are used. (Figs. 318 to 321.) This construction

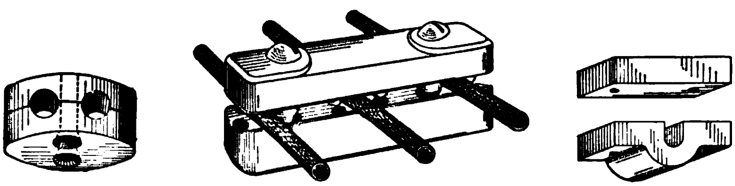


Figs. 318–321. Porcelain Knobs.

seems to be open to the same objection as the use of wooden cleats, the wires being entirely exposed between the points of support. Nevertheless, as already stated, this construction is practically the only one allowed for high-tension circuits (over 450

volts) inside of buildings. The explanation of this apparent anomaly is found in the fact that high-tension circuits are very carefully treated when brought within buildings. For example, the primary circuit of the alternating current system is rarely allowed to run more than a few feet after it enters a building, the potential being immediately transformed down to a safe value of about 100 or 200 volts. Even in such cases the high-tension wires are only permitted in the cellar or other portion of the building not generally used; in fact, the transformer is usually placed outside of the building wherever possible. The series arc lighting circuits which are also high tension (2000 to 5000 volts) are most carefully laid when brought into buildings, the path being as short and direct as possible, and located where the wires are not likely to be touched by persons or to come in contact with anything but the insulators.

They must be rigidly supported on glass or porcelain insulators, which raise the wire at least one inch from the surface wired



Figs. 322-324. Porcelain Cleats.

over, and must be kept apart at least four inches for voltages up to 750 and at least eight inches for voltages over 750.

Rigid supporting requires under ordinary conditions, where wiring along flat surfaces, supports at least about every four and one-half feet. If the wires are unusually liable to be disturbed, the distance between supports should be shortened.

Such circuits are never introduced into buildings to anything like the same extent as low-tension wires, which run in great numbers to all parts of most modern structures. The porcelain cleat is, moreover, free from the splinters which constitute a serious objection to wooden cleats.

Glass insulators may be used instead of porcelain, but the latter is usually to be preferred because it is stronger, tougher, and less hygroscopic. The statement is often made that "any material which is non-conducting, incombustible and non-absorptive" may be used, for this or other similar purpose. In point of fact, porce-

lain and glass are practically the only available substances which fulfill these requirements; but if any other equivalent material can be found, its use would be permitted.

For concealed "knob and tube" work: the wires are run on the timbers and studding by means of porcelain knobs, and the wires tied to them by tie wires of equal insulation to the main wire. The wires are carried through the beams by means of porcelain tubes. These tubes are set in the beams by forcing into auger-holes, and are kept in place by the friction and by the head formed on one end of the tube. (Fig. 325.) All the porcelain devices must keep the wire one inch from the surface wired over, and the wires must be kept ten inches apart. They are preferably run on separate beams. They must be stretched so as to have no sag, and are to be supported every four feet, or even closer when necessary. This style of work is much used in country houses, where an installation for a ten-room house costs only about forty dollars.


Fig. 325. Porcelain Tube.

The outlets are protected by a canvas jacket called circular loom, or by a curved porcelain tube, or even one of the beam tubes may be used for the purpose.

Mill construction: in buildings of this character mains of No. 8 wire or over, where not liable to be disturbed, may be separated 4 inches, and run from timber to timber, not breaking around, and may be supported at each timber only, otherwise, the construction in Fig. 326 or the plan of running through the timbers in Fig. 327, which cut also shows a boring-tool for this work. Unless some special tool is used, the holes will not be in line, and unsightliness as well as waste of wire is the consequence.

Wires in Plaster. — Another method of concealed wiring which at one time was considered to be an ideal one, consisted in embedding the conductors in the plastering of the walls and ceilings of a building. This method could be adopted either during the original construction of the building, or in case of repairs or re-plastering. It was employed in many fine structures where the best construction was desired, regardless of the expense; but it was soon found that the detrimental effect of the lime in the plaster upon the insulating material rapidly injured or destroyed it.

Furthermore, the changing or repairing of a wire was rendered very difficult, necessitating the tearing away of the plastering, the trouble being aggravated by the fact that the exact location of

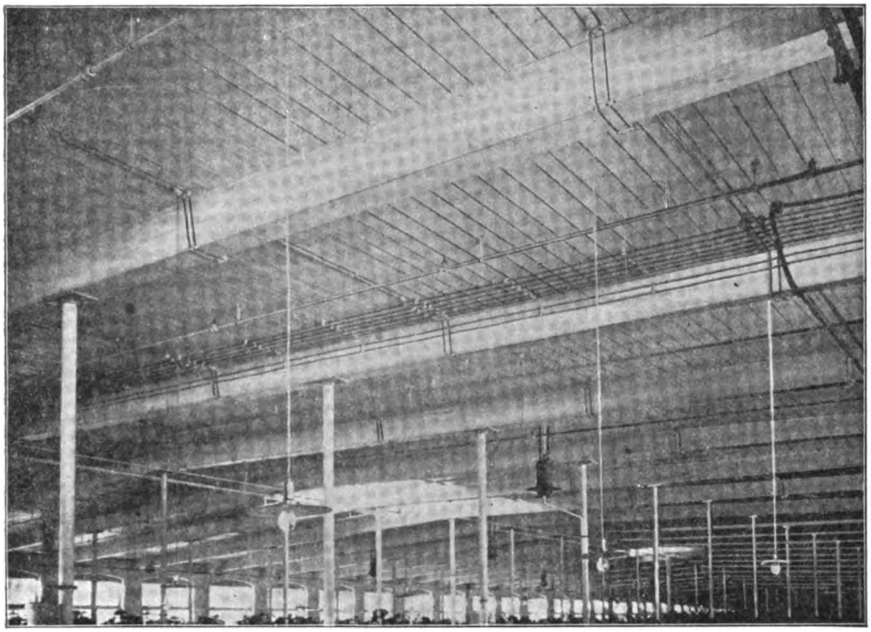


Fig. 326. Factory Wiring.

the wire was hard to determine. The result is that at the present time the National Code distinctly states "that wires must not be laid [directly] in plaster, cement, or similar finish."

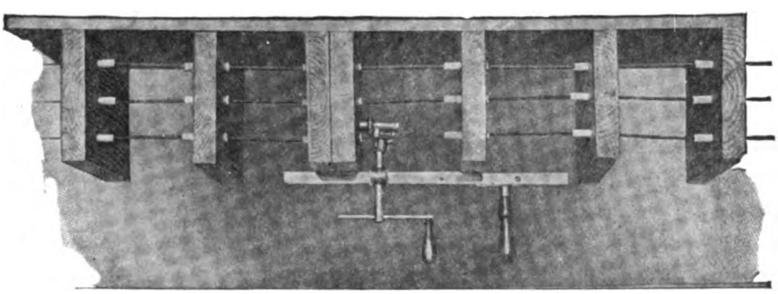


Fig. 327. Wiring through Timbers.

Interior Conduits. — The most approved method of low-tension electrical wiring consists in providing tubes, usually laid in the floors, walls, or ceilings of a building while it is being erected, in

the same general manner that gas-pipes are put in. The wires are drawn into these conduits when the building is nearly completed. It is interesting to follow the development of this standard form of construction. At first interior conduits consisted of tubes of insulating material, that is, vegetable fiber impregnated with resinous matter. Experience showed that this insulating tube was likely to be crushed or perforated by nails, either during the construction of a building or afterwards. Hence the next step was to protect the insulating tube with a thin sheathing of brass, giving the so-called "brass-armored conduit." Even this was not found to be an adequate protection against mechanical injury; so that an iron or steel pipe, about equal in strength to an ordinary gas-pipe of the same diameter, was substituted for the thin brass sheathing, producing the well known "iron-armored conduit." The final stage of the development was reached when the National Electrical Code of 1897 allowed the use of plain iron or steel pipes as conduits, "provided their interior surfaces are smooth and free from burrs; pipe to be galvanized, or the interior surfaces coated or enameled, to prevent oxidation, with some substance which will not soften, so as to become sticky, and prevent wire from being withdrawn from the pipe." This evolution clearly shows that the object of such a conduit is to facilitate the insertion or extraction of the conductors, to protect them from mechanical injury, and as far as possible from moisture. These tubes or conduits are to be considered merely as raceways, and are not to be relied upon for insulation between wire and wire or between the wire and the ground. On the other hand, the presence of a lining of insulating material is undoubtedly an advantage in most cases, and it would probably be worth the extra expense that it involves. The permission of the National Code to use plain iron or steel tubes in no way implies that they are better than insulated conduits. It simply means that the general use of some form of conduit is to be encouraged, and to this end restrictions are removed as far as possible.

The various styles of house conduit, such as brass-armored, paper-lined tube, etc., have been gradually discarded; and the standard conduit of the present time is either iron pipe with an inner insulating lining, or iron pipe with an enamel finish inside and out. The objection to rubber compound insulating lining is

the fact that if the pipe is subjected to any heat, owing to its being in a hot boiler-room or other location where there is an unusually high temperature, the insulation somewhat deteriorates, and renders it very difficult to pull out old wires and replace them with new ones. The enamel conduit is rapidly growing in favor, owing to the fact that it forms a good raceway for the wires, and it is not subject to the above-mentioned disadvantage of the insulated conduit.

Electro-duct, Armor-duct and Loricated Pipe conduits are iron pipes with the inner and outer surfaces covered with enamel, whose service is to render the conduit rust-proof, as rust is highly injurious to rubber, which is the insulation used on wiring in interior conduits.

There are many conduits having an insulated lining, such as *Armorite and Iron-armored* conduit (Fig. 328). These insulations are of paper, wood-fiber impregnated with a moisture repellent, or are of some bituminous compound. There is also a form of conduit which is lined with vitrified clay pipe.

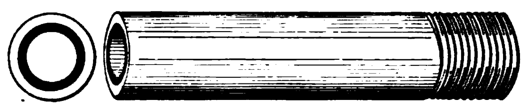


Fig. 328. Insulated Iron-armored Conduit.

"Fished Wiring." — In order to avoid the unsightliness of exposed wiring, various methods of concealed wiring have been in vogue. The obvious plan of running conductors through the spaces in walls, floors, etc., of buildings, has been followed from the first. In one method of doing this, the wire is pushed or drawn by hooks from point to point, trusting largely to chance. Hence the process of introducing it is called "fishing." This haphazard method of laying wires is not to be recommended, since it is evident that the wires may come in contact with nails, steam and gas pipes, sharp edges of beams, etc., which might cause serious difficulties. In some cases, however, it may be the only practicable way to carry a conductor from one point to another. In this case the attitude of insurance authorities on the matter may best be shown by quoting from the National Electrical Code, Rule 24, C and S. "Wires must not be fished for any great distance, and only in places where the inspector can satisfy himself that the rules have been complied with. When from the nature of the case it is impossible to place concealed wiring [in conduits

or in the regular way] on non-combustible insulating supports of glass or porcelain, the wires, if not exposed to moisture, may be fished on the loop system if incased throughout in approved continuous flexible tubing or conduit." The method of "fishing" wires should never be attempted for high-tension conductors.

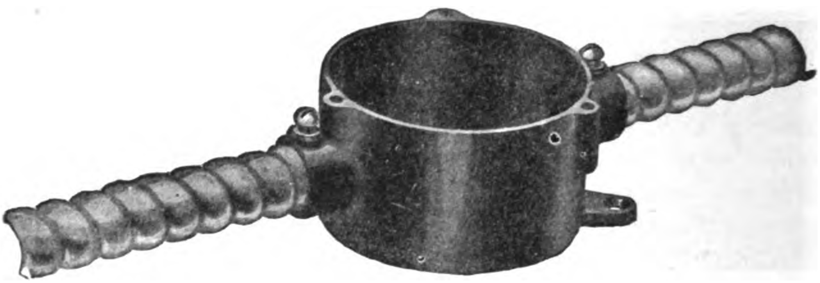


Fig. 330. Junction or Outlet Box for Flexible Conduit.

This flexible conduit may be a flexible steel tubing composed of convex and concave steel ribbons wound in a spiral around a mandrel so as to interlock. Its use is permitted by the underwriters for either finished or new houses. This tubing is not water-proof; and some difficulty is experienced in getting the wire through it, owing to the fact that it is heavy, and sags somewhat between the points of support. The tubing is made in lengths of 100 feet, and is intended to be installed without joints between outlets. An outlet box and portions of the tube are shown in Fig. 330, and an iron clamp for turning a right angle in Fig. 331.

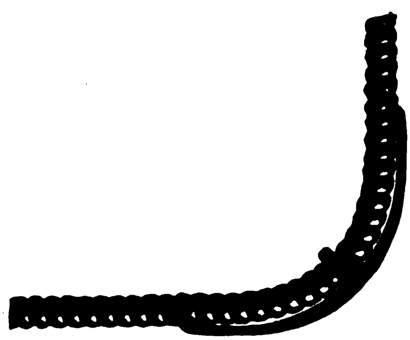


Fig. 331. Flexible Metallic Conduit.

Circular loom, or canvas jacket, is a tubular woven fabric treated with compound, and rolled in mica dust while yet soft. This is sometimes used, one tube for each wire, in finished houses where the wires are fished.

Wires unprotected and fished between walls are not allowed under any circumstances.

Flexible Iron-armored conductors have come into the market,

and are successfully used for repair-work, and in places where the conductors are exposed, as in "drop cords" for example.

Installation of Interior Conduit. — All conduits should be continuous from one junction box to another, or to the fixtures, and the conduit tube should fit properly into all the fittings, else the conductors are not properly protected, and water is much more likely to enter the conduit. The entire conduit system of a building should be completely installed, and the mechanical work on the building finished before the wires are drawn in. In the houses which are not fire-proof, tubing is generally supported from the underside of the floor beams, while in buildings of fire-proof construction they run on top of floor beams and under the finished floor.

The tubing of houses is generally put up as soon as the partitions have been erected; and when the tubing and outlet boxes have been placed, the lathing or plastering is proceeded with. On the completion of the plastering, the wire is pulled in, and switches, receptacles, etc., put in position.

After all the conductors have been drawn in place, the outlets should be plugged up with a wood or fiber plug, made in parts to fit around the wire, and the outlet painted with some compound. The aim should be to make the whole system air-tight and moisture-proof.

The final test is then made to see that there are no grounds on the different parts of the wiring, and that the insulation resistance is sufficiently high to conform with the underwriters' requirements.

The metal of all conduits should be effectually and permanently grounded. It is impossible to prevent the conduit from being partially grounded, and hence it should be purposely and completely connected with the earth.

Conduit Wiring. — Standard rubber-covered wire should be used, because there is always the possibility of dampness getting into the conduit; and the insulating lining of the conduit, if there is one, may be defective in places. The insulating lining of all conduits may be said to be defective, in that it is not continuous, but must be cut at each of the couplings.

Conduit work is made a complete system by the use of outlets, junction boxes, and panel boxes with doors and locks, thus thoroughly protecting the circuits at all places.

There are two types of outlet box. One where the box is made for a given position and number of outlets (Fig. 332), and the other where the number of outlets to the box is variable. In this

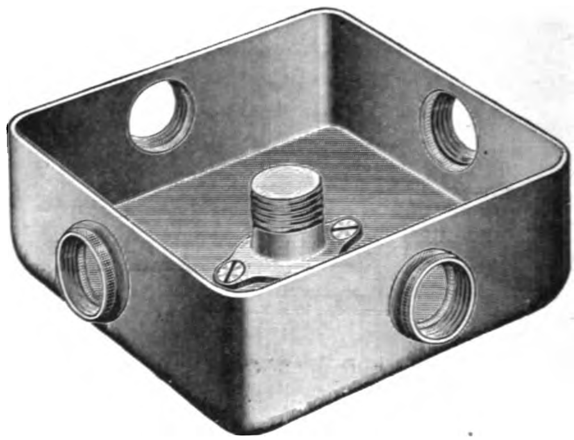


Fig. 332. Outlet Box.

latter type the sides are made in such a manner that a blow of a hammer will knock out a disk of metal and make an outlet. These are called Universal boxes.

Control. — In connection with the systems of wiring that have been explained, there is the system of control, that is the same for all.

From the switch board, which may, according to the size and character of the installation, vary from a combination of marble panels to an asbestos-lined, hardwood box, the feeders run to the channels provided, and are carried to the various parts of the building. As a rule one pair of feeders for each floor is sufficient.

Feeders are the conductors that carry the main currents to feed the branch circuits and mains. They also preserve the regulation by bringing various points of the installation to a certain predetermined potential. The feeders must be designed to carry any load that may be legitimately put upon them. A usual method of calculating their size is to assume the load to be 80% of the total load that can be brought on them, and then, with that current, design for about 2% loss of voltage. This figure can in small plants, due to the short length of the runs, be reduced to 1.5%.

Each feeder will run directly to a panel board. These boards

vary from marbleized slate to asbestos-covered wood. The better kinds are inclosed in a panel box lined with slate, and furnished with a door and a lock. Double-pole "baby" knife switches and fuses are placed on the panel board. The space between the lining of the box and the panel board proper is known as the "gutter." The conduits of the various tap-circuits enter this gutter, and the wires are protected from the ends of the conduit by bushings. All wires in the gutter are inclosed in flexible tubes, and connections are made on the panel-boards by means of the switches between the feeders and the various pairs of mains supplied by them.

Mains and Taps. — From the panel board the mains run to cut-out boxes; and there the mains branch out into the taps, going to the outlets and supplying the lights. These circuits are designed for a 1.5% loss, and in small installations may be brought down to 1%. This gives in large plants with long runs a total voltage loss of about 3.5%, and for smaller plants about 2.5%.

The lights will be supported on a fixture or a drop cord, and will usually be controlled by a key socket.

From this it will be seen that there may be from the service to the lamp the following succession of conductors and safety devices:

Service connection, service wire, double-pole cut-out, double-pole knife switch, trunk-line to switch board, double-pole knife switch, fuses to protect the feeder, feeder to distributing panel box, double-pole baby knife switch, fuse to protect the main, main to the cut-out box, plug or inclosed fuse to protect the branch, taps to the outlets through single-pole snap switch to control light or group of lights, wire to the fixture or rosette, fixture wire to socket, key switch in the socket, and finally the lamp, as indicated in Fig. 333.

The number of tap-circuits will be determined by the underwriters' rule that no group of lights requiring more than 660 watts shall depend on one cut-out. Fuses and cut-outs must not be concealed in the canopies or shells of fixtures.

Another rule of the underwriters requires a fuse to be placed at every point where a change is made in the size of the wire, unless the cut-out in the larger wire will protect the smaller. It is well, therefore, to lay out the wiring so that while obeying this rule there will not be too many fuses in series located at different points, which always cause delay in case of trouble.

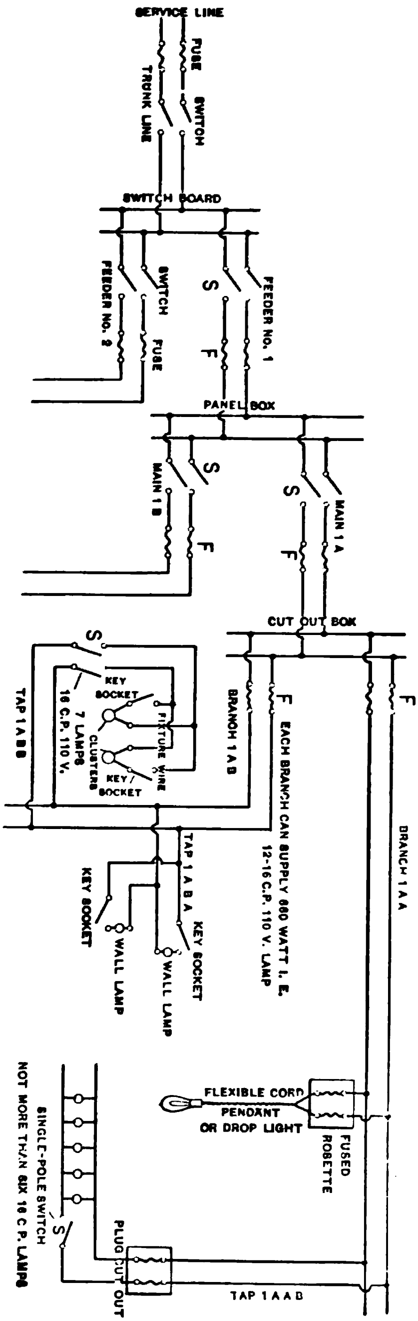


Fig. 335. Scheme of Interior Wiring.

The number of *fuses in series* must be kept down to the minimum, and they should be centralized as far as possible to aid the rapid location and replacement of the fuse, in case it blows.

In the calculation of wiring the following simple formulæ will be all that is necessary for the direct current system and for the secondary wiring of alternating systems.

$$cm = \frac{10.8 \times 2d \times c}{v}.$$

$$r = \frac{v}{2d \times c}.$$

c.m. = circular mils.

d = the distance, i.e. the length of wire in feet on one side of the circuit between the points in question.

c = load carried by the wire in amperes.

v = volts to be lost in the line.

r = resistance per foot of the wire to be used.

10.8 = resistance of one mil-foot of commercial copper at 75° F.

When the circular mils or the resistance per foot of the wire has been determined, find the size of the wire to be used by reference to the table on page 8, taking the nearest size larger than the wire as calculated. Then refer to the table

on page 15 to see if the current that is to be carried is below the allowable value.

Safety Devices in interior wiring are of special importance, since the inconvenience of repairing circuits is great, and the consequences of overheating wires by excessive current are likely to be very serious. On *series* circuits some form of *cut-out* (p. 25 and p. 340) is applied to each lamp to *short-circuit* it if by accident it tends to interrupt the circuit. In this case the *continuity* of the circuit must be preserved since the voltage is usually very high, and a long, dangerous arc would be formed if attempt is made to open it at any point. Furthermore, there is little risk of the current (in amperes) varying much from its normal value, since a special regulator is provided (p. 171, p. 186 and p. 189) to maintain a nearly constant current.

On the other hand, *parallel* distribution, usually operating at practically constant potential, requires the main conductors as well as each branch to be protected by a device that will *open* the particular circuit whenever the current in it tends to become excessive. In this case the number of amperes is inversely proportional to the resistance of each branch circuit.

If this resistance is reduced abnormally by a leak or short circuit between the + and – conductors, the current may rise to many times its safe value, and the wires may be greatly overheated, even to the fusing point, since the heating effect increases as the square of the current. For protection against this danger, fuses and circuit-breakers are employed in large numbers, there being hundreds of the former in any parallel system of distribution of even moderate size. These two devices are discussed in Vol. I. Chap. XXII., but it will be well to supplement that general discussion by considering the particular forms used in connection with interior wiring.

In principle, *safety fuses* are weak links purposely introduced into the circuit, and intended to melt and open it if the current tends to exceed a certain safe limit. Lack of confidence in fuses is often expressed by those who have had much experience with them ; but on account of their simplicity and cheapness they are used almost universally except on switchboards or in connection with motors, or in other special cases where the importance of the circuit or the likelihood of its being overloaded are sufficient to

warrant the use of circuit-breakers. For the numerous branch circuits in electric-lighting, carrying only a few amperes each, it is practically necessary to adopt fuses. Furthermore, it is a fact that the use of fuses of standard lengths and cross-sections under definite conditions will give uniform and reliable results. Formerly the length of the fuse wire was not defined, and it was sometimes open and sometimes inclosed so that it might carry much more current in one case than in another.

The principal forms are *link*, *plug* and *inclosed fuses*. A standard type of link fuse block made of porcelain is illustrated in Fig. 334, and the fuse itself in Fig. 335. These are suitable for

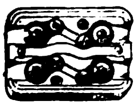


Fig. 334.

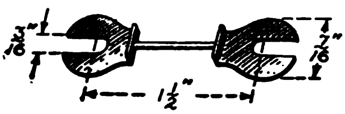


Fig. 335.

circuits having a potential not exceeding 125 volts across one fuse link and a maximum capacity of 75 amperes. Larger and heavier blocks are made for greater capacities, and are provided with mica sheets as covers. This form requires the use of a screw-driver in replacing a fuse, and this in unskilled hands, or even in skilled ones, may by accident cause a short circuit.

In Fig. 336 is shown the Edison porcelain *plug cut-out*. These have a maximum current capacity of 30 amperes and a maximum potential of 125 volts across one fuse. The fuse is contained in a screw plug, shown in Fig. 337. When a fuse has blown, the plug is unscrewed and a new one put in its place. This is a very simple and safe operation, even if the short circuit still exists when the new plug is screwed in.

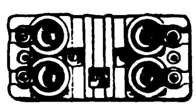


Fig. 336.

Fig. 337. Edison Plug Cnt-Oat.

The *inclosed fuse* represented in Fig. 338 possesses the same advantage in convenience and safety of renewal. It is also claimed to be more definite in its action, since the conditions are more nearly uniform than in the case of open or partly open fuses. Still another advantage is the fact that a fuse closely surrounded with solid, fibrous, or powdered material, has a greater capacity for heat than if it were isolated. Consequently it requires a little longer time to reach the fusing point, and an excess of current must be very great in amount, or must flow for an appreciable time, in order to "blow" the fuse. A current that only momentarily exceeds the normal will not injure the wires or apparatus, and it is simply a nuisance to have it open the circuit. The form of fuse illustrated in Fig. 339 is very conveniently replaced, and is also capable of being used as a sort of switch to open and close the various circuits. It is provided with a copper blade at either end, which fits into clips just as in an ordinary knife switch. A similar arrangement is shown in Fig. 340, the fuses being carried in porcelain boxes with projecting blades that are pressed into the clips in the cut-out cabinet.

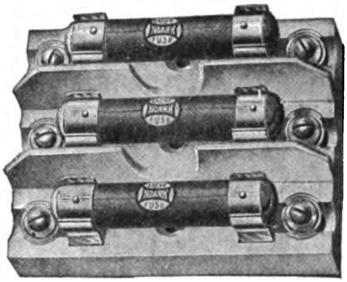


Fig. 338.

Fig. 339.

Circuit-Breakers. — These devices are shown and described in Vol. I. Chapter XXII., and belong more to the generating plant and switchboard than to interior wiring. Essentially they are switches that are controlled by an electromagnetic device so as to open automatically when the current exceeds a certain limit. They are much

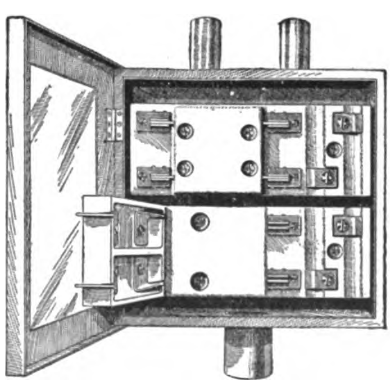


Fig. 340.

more accurate in this respect than a fuse, and can be adjusted to act at any given current within a considerable range. Their accuracy and adjustability are important, but their great advantage over the fuse is the facility of resetting them compared with the trouble and delay of renewing a fuse. The fact that a circuit-breaker flies open the instant that the current rises above the value for which it is set, may be a doubtful advantage. This might happen very often when the excess of current does not last long enough to cause any harm, as explained in connection with fuses on the preceding page. The main circuit-breaker may open at the same time as one in a branch circuit, thus shutting off other parts of the system needlessly. In some forms the so-called time factor is purposely introduced, a device being added to prevent action unless the overload is of a certain duration. An example of circuit-breaker illustrated in Fig. 341, differs from most types in the fact that the arms for the two sides of the circuit are independent, so that one may open automatically if it is attempted to close the other while a short circuit still remains.

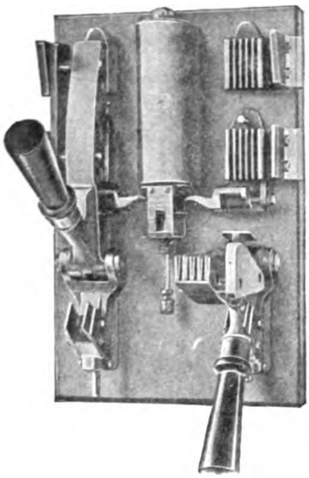


Fig. 341. Automatic Circuit-Breaker.

Switches. — The general facts concerning these important devices are set forth in Vol. I. Chapter XXII., but there are certain additional points to be noted in connection with interior wiring. The rules for switches as laid down by the National Electrical Code will be found on pages 9, 10 and 23 of the Appendix to the present volume. Ordinarily the type used on switchboards is the simple lever *knife-switch*. They are sometimes made in the *quick-break* form in order to reduce the duration and therefore the burning effect of the arc produced on opening the circuit. It is a fact, however, that switches are used to *close* the main circuits or those carrying heavy currents, but should not be used to open them except in emergency. In starting up an electrical plant, or in closing the service switch of an installation, the switches controlling the various circuits may be closed before or after the current is

turned on, and a switch may be left open if no energy is required in the corresponding circuit. In case of overload, a circuit-breaker or fuse should be provided in each main or branch circuit to open it when the current exceeds a safe value, but the switch itself when carrying heavy current is to be opened only as a last resort. Under ordinary circumstances the lamps are disconnected in comparatively small groups by means of snap switches, one of which is shown in Fig. 342. In fact, the current allowed in each branch circuit is limited by the insurance rules, being a maximum of 660 watts (equivalent to 12 lamps of 16 c.p. each at 110 volts). Even in a theater or other place where many lamps are turned on or off at about the same time, it is customary to control them in groups, each having a separate switch. If the current does not exceed 3 amperes at 110 volts a single-pole switch is allowed, but for currents greater than this it must be double-pole.

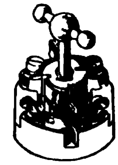


Fig. 342.—Snap-Switch.

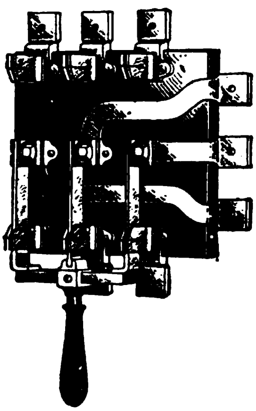


Fig. 343. Break-down Switch.

Break-down Switch. A building having its own generating plant may be provided with a connection to the street circuit of some electric lighting company. In case of accident to, or repair of, the isolated plant, current may be obtained from the central station. The switch which enables this to be done is called a "break-down" switch, since it is used in case the local machinery is broken down. It is usually of the double-throw type (Fig. 343); and since street circuits are often three-wire systems, and isolated generating plants are operated in most cases on the two-wire plan, the switch is generally arranged to convert from the former to the latter, as described on page 82.

Multi-Control Switches. It often happens that it is desired to light or extinguish a given lamp or group of lamps from two or more different points. A common case is that of a lamp which may be turned on at the foot of a staircase and turned off at the top, or *vice versa.* This may be accomplished in various ways: one plan indicated in Fig. 344 requires a three-way key socket at the lamp, a three-way switch at the other point of operation, and an

extra wire between them in addition to the two mains that supply the current. With this arrangement the lamp may be lighted or extinguished by either switch.

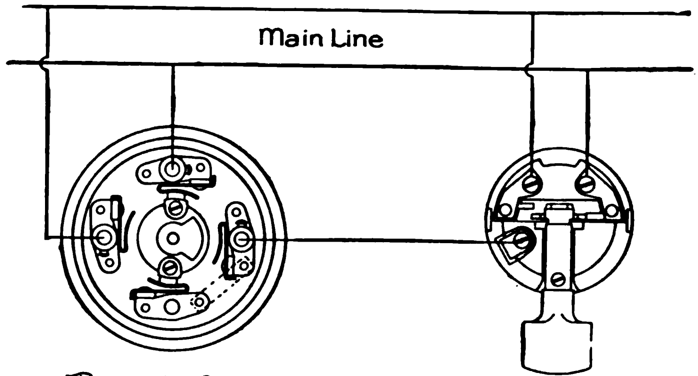


Fig. 344.

Panel Boards and Cut-out Cabinets are miniature switch-boards or sub-centers of distribution which afford means of splitting up the mains into branches and of grouping the cut-outs. The various forms used differ mainly in the styles of switches or cut-outs and

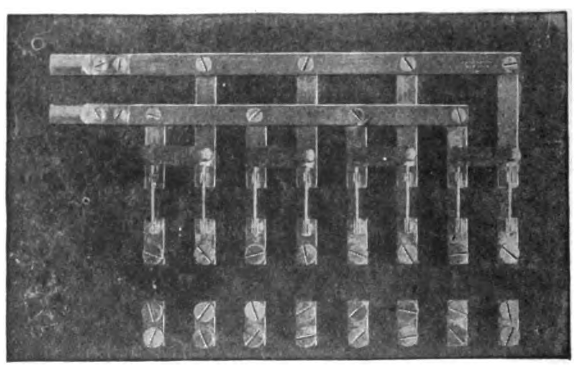


Fig. 345. Panel Board.

in their arrangement, as illustrated in Figs. 340, 345 and 346. The two or the three main conductors are represented by parallel wires or bars of metal, from which the branch circuits are led out through switches and cut-outs.

Fixtures and Sockets. — The endless variety of fixtures used for supporting arc and incandescent lamps may be classed as furniture

or ornament, as they are not of a character to be included in a technical treatise; the only technical features they contain being the fixture wiring and the insulated joint interposed between the fixture and the gas-pipe to which it may be attached. The sockets are described in the next chapter, on Incandescent Lamps. In a general treatise it is impossible to go into the details of interior wiring, as they depend largely upon the conditions in each particu-

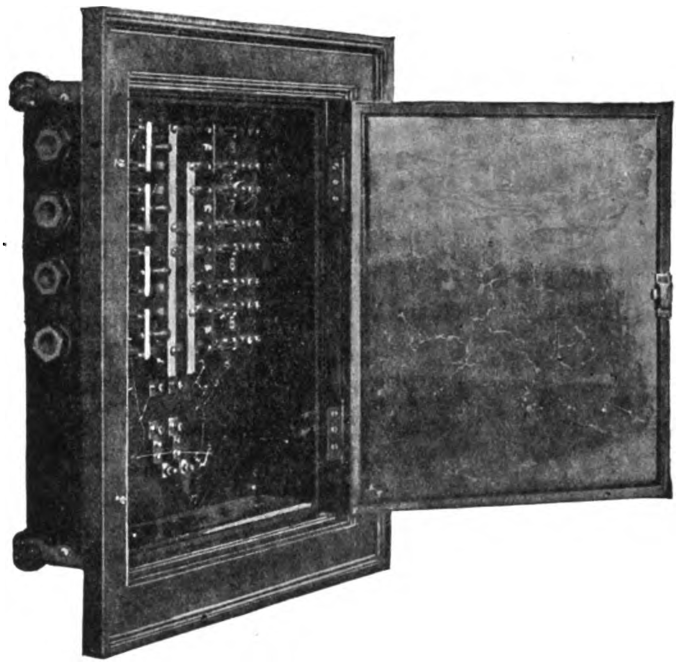


Fig. 346. Cut-Out Cabinet.

lar case. The principles involved and the chief elements of construction have been set forth, and for further information reference may be made to the National Electrical Code printed in full in the Appendix and to the following publications: —

Cushing, H. C., Jr., *Standard Wiring for Incandescent Light and Power*, pp. 116, N. Y., 1900.

Emmet, W. L. R., *Alternating Current Wiring and Distribution*, pp. 76, N. Y., 1898.

Leaf, H. M., *Interior Wiring of Buildings*, pp. 195. London, 1899 (gives English Practice).

Noll, A., *How to Wire Buildings*, pp. 162, N. Y., 1899.

Pierce and Richardson, *National Electric Code* (Explanation of), pp. 222, N. Y.

Robb, R., *Electric Wiring*, pp. 183, N. Y., 1896.

A series of articles on *Interior Wiring*, by Charles E. Knox, in the *American Electrician*, N. Y., 1898 to 1900.

CHAPTER XVII.

INCANDESCENT LAMPS.

An incandescent electric lamp is one in which light is produced by the passage through a solid conductor of a current sufficiently strong to raise it to a temperature of incandescence. In this case the conductor is solid and continuous, while in an arc lamp, the other important type described in Chapters XIV. and XV., light is produced at a gap in the circuit across which the current is carried by the heated vapor present. The ordinary type of incandescent lamp, enormous numbers of which are now used, consists essentially of a high resistance carbon filament hermetically sealed in a nearly perfect vacuum. In fact, these words are substantially the same as the patent claims of Edison,* who developed the incandescent lamp as well as the necessary generator method of distributing current and the various auxiliary devices to a condition of commercial success.

Many forms of incandescent lamp have been devised employing filaments composed of materials other than carbon, and not requiring a vacuum; but these are special types that will be described later. The present chapter is confined to the ordinary incandescent lamp, as already defined, which has been used to the practical exclusion of any other form since the introduction of incandescent lighting in 1880.

Materials Used for Filaments. — In the earlier lamps made by Edison, the filaments consisted of platinum wire, but that metal soon lost its strength, even at normal working temperature; and if accidentally raised above this point it was likely to be melted. The high cost of platinum is also a serious objection to its use for this purpose. Consequently Edison soon substituted carbon for platinum in his lamps. After trying many materials, carbonized

* U. S., Patents, 1879.

bamboo was adopted, and generally used in the Edison lamps made for about fifteen years. Other manufacturers employed thread, thin strips of cardboard, or some special compound in place of bamboo. In practically all cases some organic substance carbonized by heat has been used.

For several years the tendency has been to adopt almost universally the so-called "squirted filaments." They are usually made by dissolving cotton in a solution of zinc chloride producing a viscous, semi-transparent liquid in which the appearance and fibrous character of the cotton are entirely lost. This gelatinous material is forced or squirted through a small hole, and received in a vessel containing alcohol, which causes it to set and harden sufficiently to be handled afterwards. After washing, the material, having the appearance and consistency of cooked vermicelli, is wound upon a large drum and dried, after which it possesses considerable strength, and looks much like a cat-gut string such as is used on a violin. It is then cut into lengths suitable for filaments, and carbonized at a high temperature.

The advantage of using this product in place of some solid substance, such as bamboo, is the fact that it is perfectly homogeneous, and can be made readily and accurately of any desired cross-section or length. On the other hand, there is considerable difficulty in eliminating entirely bubbles of air from the viscous solution of cotton. If they are present, even though very small, they will cause a flaw in the filament at any point where a bubble may happen to exist. In order to get rid of them the solution is filtered and heated under a vacuum. To avoid the presence of impurities and to insure a perfectly homogeneous product the best quality of cotton wool should be used, the specially high grade employed by surgeons as absorbent cotton being adopted by the best manufacturers. Great skill and care are required in making the mixture, the exact density and temperature of the zinc chloride solution as well as the proportion of cotton dissolved in it being matters of particular importance. The formation of lumps in the jelly-like mass is likely to occur, and should be prevented by constant stirring, otherwise the resulting filaments will not be of uniform cross-section.

Measuring and Sorting the Filaments. — After being carbonized, the filaments are carefully measured and sorted according to

length and diameter. The latter is reduced very greatly by the processes of drying and carbonizing, so that it must be determined very exactly by means of a micrometer. A filament made from "squirted" cellulose solution is somewhat elliptical in cross-section owing to its having been wound, while soft, upon the drying-drum. For this reason it is necessary to measure both maximum and minimum diameters in order to determine its true cross-section. The filaments suitable for the various types and sizes of lamps are thus selected. In a general way the length is proportional to the voltage, and the surface is proportional to the candle-power for which the lamp is intended.

Flashing or Treating the Filaments. — The object of this process is to render the filaments stronger and more uniform. Formerly, when they were made from bamboo, thread, and similar materials, the filaments obtained were far from uniform throughout their length. The present forms of "squirted" filaments are better in this respect, being more uniform in diameter and more homogeneous; but even these require to be treated after being carbonized. The treatment consists in raising the filament to incandescence by passing through it an electric current in an atmosphere of hydrocarbon vapor or gas.

The high temperature of the filament decomposes the hydrocarbon, and causes carbon to be deposited upon it. This deposit occurs over the entire surface of the filament, but is greater at any point where the electrical resistance may be abnormally high, because the temperature there will also be higher. Hence the tendency is to produce a filament of uniform resistance throughout its length. In the same way the strength is made more uniform, because any part thinner or weaker than the rest is likely to have a higher electrical resistance, so that it will be reinforced by receiving a heavier deposit of carbon. On the other hand the deposited carbon is graphitic in character, and has a lower specific resistance of 10 to 15 per cent that of the original filament, which is undesirable especially for high voltage lamps.

The filaments are treated after they have been carbonized, but before they have been mounted, the process being performed in a jar containing hydrocarbon vapor. The stopper of the jar carries metallic holders into which the ends of a filament are inserted, the latter being then introduced into the jar. By means of the

metallic holders which serve also as electrical connections, a current is caused to flow through the filament in order to bring it to incandescence. The resulting deposit of carbon reduces the resistance until a certain value is reached, when the current is interrupted, and the filament is taken out, to be followed by another and so on. The proper resistance is predetermined by experience or calculation for each type of lamp. It may be measured during the process of treatment by disconnecting the filament from the current supply, and connecting it to some resistance measuring device, such as an ohmmeter, a double-throw switch being used to make the change. In this case the measurement is made while the filament is cold, and it is generally assumed that at working temperature the resistance is reduced one-half. It is also an easy matter to determine the resistance when the filament is incandescent, and the carbon is being deposited upon it. By measuring the voltage across the terminals of the filament and the current flowing in it, we know from Ohm's law that ohms = volts ÷ amperes. In another method the filament is made one arm of a Wheatstone bridge, and the other three resistances are so adjusted that no current flows in the galvanometer circuit when the filament reaches the proper resistance. A relay put in place of the galvanometer will release its armature at that moment, and may be arranged to stop automatically the current through the filament. The increase in diameter resulting from the deposit of carbon is about 10 per cent, but varies in different sizes and makes of filament.

Mounting the Filaments. — In order to mount the filaments, that is, connect them to the "leading-in" wires (*C C* in Fig. 352), that are to supply them with current, various methods have been devised and used. One plan consists in *electroplating* a sleeve of copper around the end of the filament and of the wire, thereby mechanically binding and electrically connecting them together. In lamps formerly made from carbonized cardboard, the ends of the filaments were enlarged so that they could be attached to the ends of the wire by very small bolts. Another method consists in forming a *socket* at the end of the wire into which the end of the filament is inserted, and held in place by squeezing the socket around it. These means of connection have been in most cases abandoned for the simpler and cheaper joint, made by *pasting* together the ends of the filament and wire, using a

mixture of powdered carbon and molasses, or other similar sticky material. Still another form of joint is made by heating the junction of the filament and the wires by an electric current in an atmosphere of hydrocarbon gas or under a hydrocarbon liquid. In this way a deposit of solid carbon is formed around the filament and wire, which binds them together. The deposit takes place more rapidly in the liquid, but the latter is objectionable because it adheres to the filament and wires. This so-called *deposited carbon joint* is a very good one, but is more troublesome and expensive to make than the *pasted joint.*

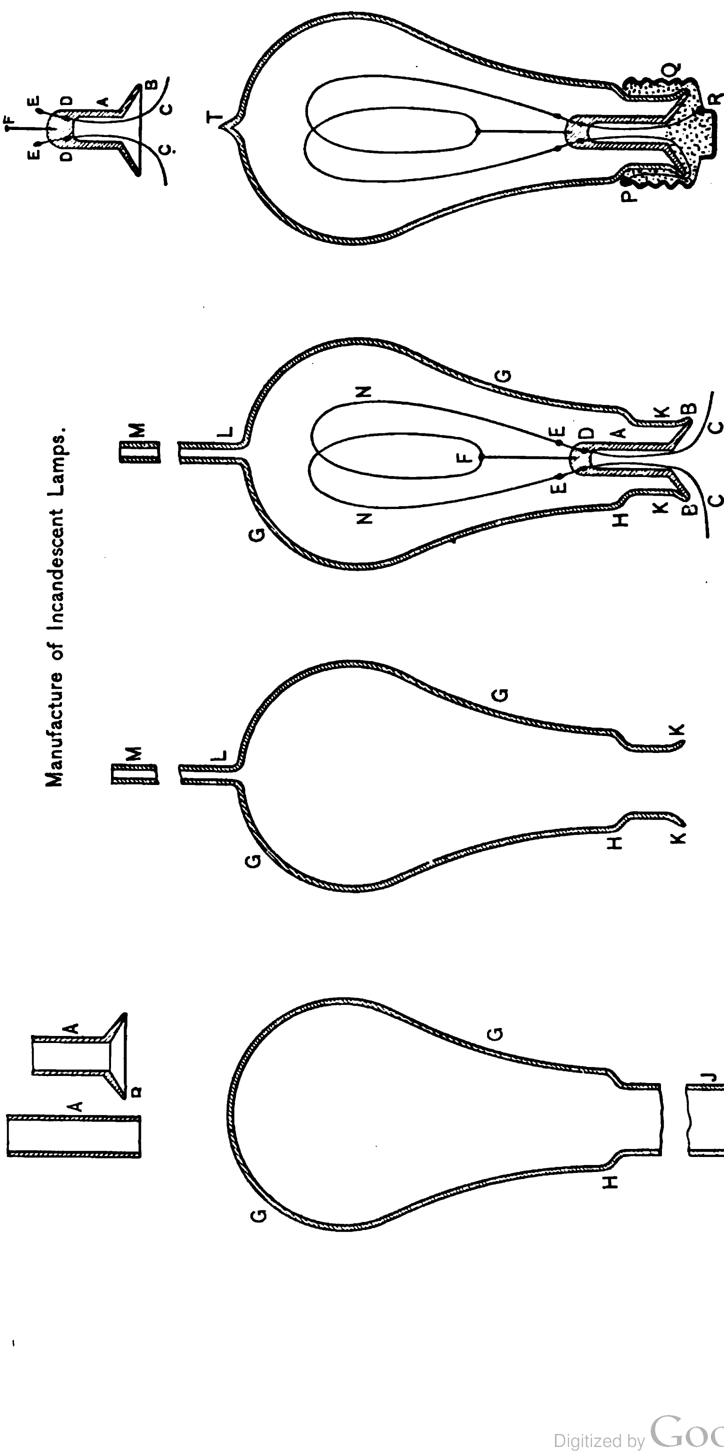
Platinum "Leading-In" Wires. — To insure a perfectly air-tight seal where the "leading-in" wires pass through the glass, they are made of platinum, because its coefficient of expansion by heat agrees with that of the glass which is used. If the two coefficients of expansion differed materially, it is obvious that there would be a tendency either to crack the glass or to let in air when temperature changes occurred.

Platinum being a very expensive metal, even the small amount required in an incandescent lamp is a considerable item in the cost, so that many attempts have been made to substitute some cheaper metal or alloy. While alloys having about the same coefficient of expansion as that of glass can be made, they are open to the objection of not being able to stand the high temperature of melting glass or the action of the blowpipe flame without melting or burning while being sealed in, so that there is likely to be a leak owing to the imperfect fusing of the glass to the wire.

In order to economize as much as possible in the cost of platinum for each lamp, the greater portion of the length of the leading-in wires is composed of copper, platinum being used only where the wire passes through the glass. For example, in Fig. 352, the longer parts, *D C*, of the leading-in wires are of copper, and the shorter parts, *D E*, are of platinum, the joints between the two being made by electrical welding.

Glass Portions of Incandescent Lamps. — The several steps in their manufacture are indicated in Figs. 347–353, a standard Edison 16 *c. p.* lamp being represented on a half scale. To form the "inside part," a glass tube *A* is used, being first softened by heat and flared out at one end *B*. The other end is then softened, the leading-in wires *C E* introduced, and the plastic

Manufacture of Incandescent Lamps.



Figs. 347–353.

glass is pinched around the wires at *D D* so as to form a hermetical seal. If the filament is to be of a form to require it, an anchor *F* is introduced at the same time. The next step is the making of the bulb *G*, which is simply blown on the end of a glass tube *H J*, in the ordinary way. The extreme end of the bulb is then heated by a blow-pipe, and a small glass tube *L M* is attached to it at that point. The bulb is now disconnected from the tube *J* by melting the latter around at *K* and pulling the two apart.

The inside part *A* upon which the treated filament *N* has been mounted by means of pasted joints at *E E F*, is next introduced into the bulb *G*, and the two are united by fusing together the circular edges *B B* and *K K*. The partially completed lamp is now ready to be exhausted of air through the tube *L M*.

The Objects of the Vacuum produced in the bulb of an incandescent lamp are:

1. To avoid the combustion of the carbon filament.
2. To reduce wear on the filament due to "air-washing."
3. To diminish the loss of heat from the filament.
4. To decrease the flow of current in the space around the filament.

At various times, it has been attempted to attain the first of these objects by using an atmosphere of some gas or vapor, such as nitrogen or bromine, which it is expected will not combine with the carbon. But even a small quantity of any gas left in the bulb may tend to consume the carbon, partly by chemical combination, and partly by a mechanical action called air-washing that wears away the filament. The presence of any gas or vapor also causes a more rapid transfer of heat by conduction and by convection from the filament to the bulb. In a vacuum, on the other hand, the filament loses heat by radiation alone, so that a smaller quantity of energy is required to maintain it at a certain temperature and candle-power. Hence the efficiency is improved, being inversely proportional to the energy consumed, other things being equal. For the same reason the bulb of a vacuum lamp is cool enough to touch with the hand, even while burning, and will not ignite anything that may come in contact with it unless the heat is allowed to accumulate by leaving it for some time partly or completely surrounded by an

inflammable material, such as cloth or wood. The bulb of a lamp containing some gas becomes considerably hotter, and is therefore less convenient to handle, as well as more likely to start a fire. The "air-washing" effect is not considered to be as important as formerly, the wearing out of the filament being due chiefly to projection of particles from its surface, and chemical action upon it if any active gas is present.

The flow of current through the space around the filament is called the *Edison effect*, having been first observed by him. It is a loss of energy, since the pale bluish light that it produces adds little or nothing to the candle-power. This flow is greatly reduced when a nearly perfect vacuum is reached. In fact, lamps are tested to see if the vacuum is sufficiently high, by connecting them to an induction coil; those showing the pale glow throughout the bulb being rejected. On the other hand, the presence of any considerable quantity of gas would also stop the wasteful current, so that for this reason alone either a very high or a comparatively low vacuum is desirable. The flow of current by the Edison effect may take place without the blue glow, but Mr. J. W. Howell has shown * that the two often go together.

The blackening of the bulb which gradually occurs while the lamp is burning was found by Prof. W. A. Anthony † to be considerably less in lamps containing a slight atmosphere of bromine than in ordinary high vacuum lamps. The transfer of carbon from the filament to the bulb seems to occur as a sort of projection of particles along straight lines in a manner similar to the Crooke's effect. Hence it is quite natural that the presence of even a small quantity of vapor would interfere with the deposit by reducing the "mean free path" of the particles. The blackening of the bulb by the deposit of carbon upon its inner surface is one of the important causes in the falling off in candle-power of lamps. This matter will be considered further under the head of "Relation between Candle-Power and Age" on page 416.

The methods of exhausting bulbs used singly or in combination are as follows:

1. By means of mercury pumps.

* *Trans. Amer. Inst. Elec. Eng.*, vol. xiv. p. 27, Feb., 1897.

† *Ibid.*, vol. xi. p. 132, March, 1894.

2. By means of mechanical pumps.
3. By the so-called chemical process.

The first of these consists in connecting the tube *LM* (Fig. 352) to a Sprengel or other suitable form of mercury pump capable of producing the very high vacuum required. At first the quantity of bubbles in the tube of the mercury pump show that the air is being rapidly removed, but later the bubbles become fewer and smaller, until finally none are visible. This indicates that no more air can be drawn out under the existing circumstances, but there is still considerable gas clinging to the glass, filament and leading-in wires. The lamp is now heated by passing current through the filament or by external heat in order to drive off these gases and allow them to be removed by the pump. When the vacuum is sufficiently high, the tube *LM* is softened close to the bulb by a blow-pipe flame and drawn out to form the tip *T* (Fig. 353), thus hermetically sealing the lamp.

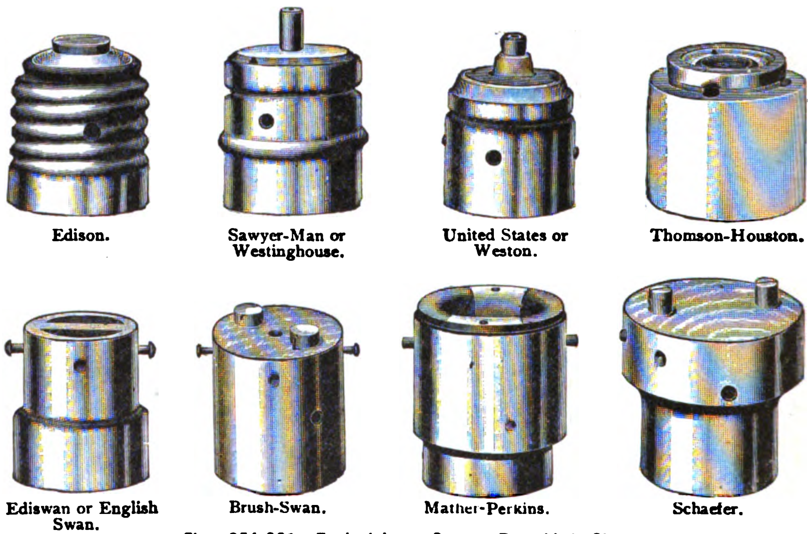
The second plan, employing a mechanical pump, is now capable of producing sufficiently perfect exhaustion for high vacuum lamps, being also used to save time and expense in removing the greater part of the air at first, when the final vacuum is obtained by a mercury pump or by the chemical process.

In the chemical process the lamp is nearly exhausted by a mechanical or mercury pump, and some substance previously introduced into the bulb is then caused to combine with the small remaining quantity of gas. In most cases a small quantity of phosphorus is put in the tube *LM*, and ignited by heat applied to the outside. It combines with the residue of gas present to form solids or non-conducting gases which are practically equivalent to a perfect vacuum. It is found that red phosphorus, which is comparatively harmless, can be used instead of the yellow form, that would be injurious to the employees who handled it.

Bases and Sockets. — The sealed lamp is now ready to receive the base which supports it, and at the same time makes the necessary electrical connections that supply it with current. Many forms of base have been used, the most prominent being the *Edison* standard type shown in Fig. 354. This consists of a brass shell formed into a screw-thread, to which one leading-in wire is soldered at *P*, and a brass button to which the other leading-in wire is soldered at *R*. To hold the parts together and insulate them from

each other, the spaces between are filled in with soft plaster of paris as indicated by dots in Fig. 353. This is allowed to harden and is then dried, otherwise the moisture would short-circuit the terminals. At present porcelain pieces are generally used instead of plaster.

The corresponding Edison socket, which is the same as that used with plug cut-outs (Fig. 336), is made with a screw-thread and contact point to receive the base of the lamp and make electrical connections to it. Simplicity and cheapness are the chief



Figs. 354–361. Typical Lamp Bases. Two-thirds Size.

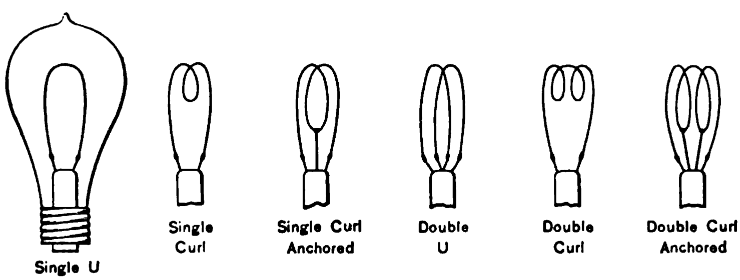
advantages of this form; and it is gradually displacing other types in this country.

The Sawyer-Man or Westinghouse lamp base, illustrated in Fig. 355, is provided with electrical contacts similar to those of the Edison type; but the lamp is held in place by inserting it in a socket consisting of spring clips or fingers which grasp it on all sides. The Thomson-Houston base has a central hole in which a thread is cut, so that it may be screwed down upon a projecting screw in the socket. The Swan, and similar bases represented in Figs. 358–360, are of the bayonet type, having small pins on the sides which fit into slots in the socket, being inserted and then turned slightly in order to lock them. All of these may be classified under the three heads of the *screw*, *clip*, and *bayonet*

types. The first class possesses the advantages that have been given for the Edison base, and the lamp may be lighted or extinguished by screwing it in or out about one turn. This is convenient in case the switch is not easily reached or is out of order. The clip or bayonet bases are not adapted to be used in this way; on the other hand, they are not so likely to work loose as the screw forms. For very large lamps, special types of socket, as in Fig. 368, are often employed.

It has been attempted to secure the general adoption of a standard lamp base and socket; but owing to patent questions, the jealousy of manufacturers, and the fact that large numbers of the different types have been installed, the effort has not been very successful in this country or abroad. Now that the original patents have expired, it would seem that this uniformity might be attained in order to save makers and dealers the trouble and expense of carrying in stock so many styles of lamps and sockets. The great variety in voltage, candle-power, form and color of bulb, and type of base, makes almost innumerable combinations that may be called for.

Forms of Filament. — The ordinary 16 candle-power lamp at 110 volts consumes about $\frac{1}{2}$ ampere, consequently its resistance must be about 220 ohms when burning. A filament having this



Figs. 362–367. Different Forms of Filament.

resistance, and sufficient cross-section to give mechanical strength and the required illumination, should be about 7 to 9 inches long. The single *U* shape (Fig. 362) was generally adopted in incandescent lamps for many years, but the excessive length of the *U*, and its tendency to droop, demand a large bulb. Furthermore, its distribution of light is poor, as explained later. To avoid these objections, the curled forms of filament are now being used almost

universally. The single curl, the single curl anchored, and the double curl (Figs. 363, 364, and 366), are common forms in lamps for 100 to 125 volts, and from 8 to 50 candle-power.

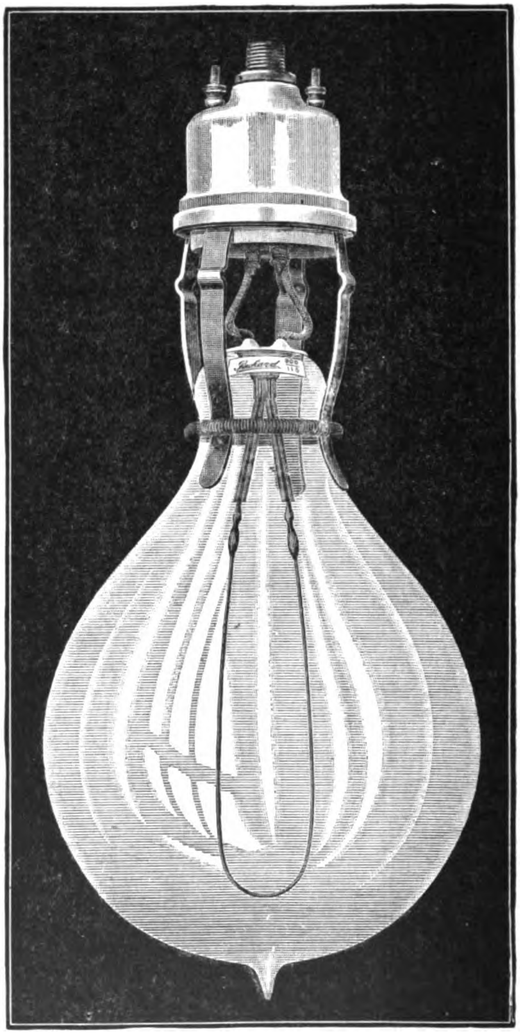


Fig. 369. Three Hundred-Candle-Power Lamp. One-third Size.

The Filament of a 220-Volt Lamp should be about twice as long as and about one-half the cross-section of a standard 110-volt filament giving the same candle-power, because the former takes

one-half as much current at twice the voltage, in order to consume the same number of watts. As a matter of fact, a 220-volt lamp requires a larger number of watts per candle-power; consequently its current is about six-tenths instead of one-half as great. The 220-volt filament, with its increased length, is usually made in the double *U* or double curl forms (Figs. 365–7), in order not to require a large bulb.

Large Lamps of 100 to 300 candle-power are usually made with the single *U* filament, as represented in Fig. 368, or with the double *U* form (Fig. 365). In this case the cross-section is much greater, the current in a 100 candle-power lamp being about six times that in a 16 candle-power lamp of the same voltage.

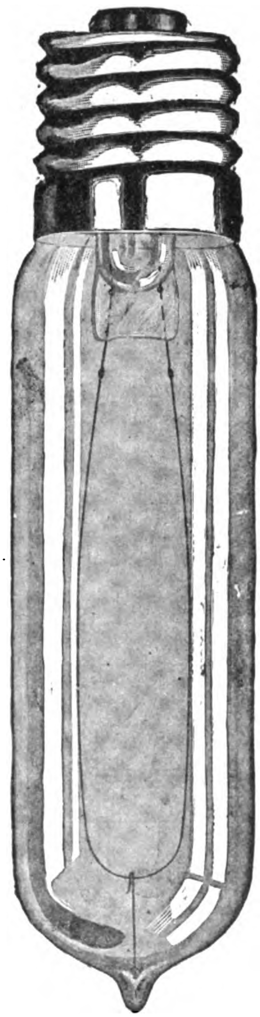
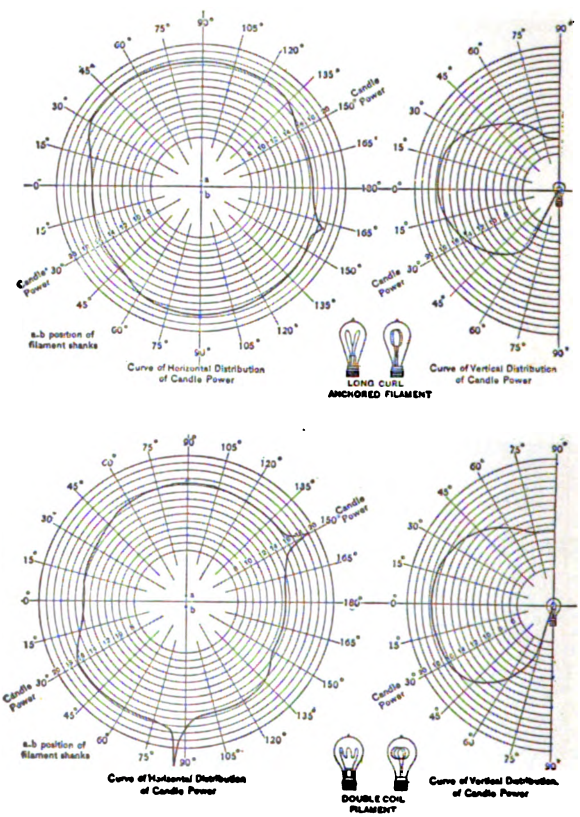


Fig. 369. Tubular Lamp.

Anchored Filaments are used when their length or the form of the bulb is such that there is danger of their touching the glass and cracking it so as to let in the air and burn up the filament. This occurs either from excessive vibration or from the gradual drooping or bending of the filament, which is likely to take place, especially when the lamp is not vertical and pointing downward. Two arrangements have already been described (Figs. 353 and 367), in which the anchors are attached to the "inner part" through which the leading-in wires pass. Another common form of anchor is sealed in the tip of the bulb, being a necessity in the tubular lamp shown in Fig. 369 to support the extreme end of the filament, and prevent it from touching the glass.

The Distribution of Light differs greatly in the various types of lamp, depending almost wholly upon the shape of the filament. The straight single *U* form (Fig. 362), giving 16 mean horizontal

candle-power, emits only 5.7 candle-power in the direction of the tip. A "long curl anchored" filament (Fig. 364), having the same mean horizontal candle-power, gives 7.05 candle-power from the tip; and a double curl filament (Fig. 366), of the same mean horizontal candle-power, gives 10.1 candle-power from the tip, showing great variations in illuminating power in different directions. The horizontal and vertical distribution of light is shown by curves in Figs. 370 and 371 for long curl anchored and double



Figs. 370, 371. Distribution of Light.

curl filaments respectively. The results for the five principal forms as ordinarily proportioned are given in the table on page 409.

A comparison of these figures shows that the candle-power measured in line with the tip is much less in the single or double *U*-shaped filament than in the single or double curl form, the mean

horizontal candle-power being the same in all cases. The obvious reason for the difference is the fact that the two former expose less surface in that direction than the two latter. By slightly twisting a *U* filament so that it does not lie in one plane, the candle-power from the tip may be increased, and by shaping it with one or two curls the distribution of light will evidently be still more uniform. It is also a fact that the tip itself intercepts, or rather reflects and refracts, some of the light tending to pass through it, so that the

CANDLE-POWER OF LAMPS WITH DIFFERENT FORMS OF FILAMENTS.

Candle-Power Taken.	Candle-Power.				
	Single U-shaped Filament. Fig. 362.	Single Curl Filament. Fig. 363.	Long Curl Anchored Filament. Fig. 364.	Double U-shaped Filament. Fig. 365.	Double Curl Filament. Fig. 366.
(*a*) Mean horizontal at 180 revolutions	16	16	16	16	16
(*b*) Mean horizontal (standard method)	15.8	16.2	16.6	16 0	15.72
(*c*) Mean horizontal (from curves) . .	16.0	16.7	16.7	16.1	15.6
(*d*) Mean spherical (standard method)	12.7	13.5	13.75	13.2	13.8
(*e*) Mean with axis at 45 degrees . .	10.5	12.0	11.7	12.0	14.0
(*f*) Mean hemispherical	14.3	14.5	14.6	14.0	14.5
(*g*) Mean within 30 degrees from tip .	8.7	10.3	8.7	7.9	10.9
(*h*) From the tip	5.7	8.35	7.05	4.8	10.1

candle-power in that particular direction is still further diminished. For this reason "tipless lamps" are made, the end of the bulb being made perfectly smooth.

On the other hand, the table shows that the mean spherical and mean hemi-spherical candle-power are very nearly the same for all five forms of filament. As a matter of fact, either of these is far more important practically and scientifically than the candle-power in any one direction, except for some special purpose, in which case a reflector may be used to throw in the direction required nearly all of the light emitted by the lamp. The facts given in Figs. 370–371 and in the table are obtained from a paper by Professor A. J. Rowland before the Franklin Institute,* in which the great importance of the light from the tip is insisted upon. In fact, he calls this the "useful light," because incandescent lamps are usually placed with the tip downward. But in many

* *Electrical World and Engineer*, Oct. 13, 1900.

cases they are arranged the other way; and even when they are not, there are reflections from the ceilings and walls, and from the globes or shades with which lamps are generally provided, so that a fairly uniform distribution of light results.

Resistance of Filaments. — The only electrical property that an incandescent lamp possesses is its resistance. The ordinary carbon filament has about twice as much resistance when cold as it has when raised to the working temperature. Obviously the latter is the important value, and absolutely determines the current and the power that the lamp will consume at a given voltage. Calling the latter V, the resistance in ohms of the hot filament R_h, the current in amperes C, and the power in watts W, we have: $C = \frac{V}{R_h}$ and $W = \frac{V^2}{R_h}$.

Ordinarily lamps of almost any size take from 3 to 4 watts per candle-power. Assuming an average value of 3.5, and that the voltage V is 110, we have from the second equation: $3.5 \times$ c. p. $= 12100 \div R_h$ or $R_h = 3457 \div$ c. p. Hence the resistance of a 16 candle-power lamp using 3.5 watts per candle-power is $3457 \div 16 = 216$ ohms, the current is $110 \div 216 = .51$ ampere, and the power is $12100 \div 216 = 56$ watts. A lamp of 32 candle-power consuming the same number of watts per candle-power has a resistance of $3457 \div 32 = 108$ ohms, or exactly one-half as much as before, the current is $110 \div 108 = 1.02$ ampere, and the power is $12100 \div 108 = 112$ watts, the two latter being twice as great as for the 16 candle-power lamp. In short, for a given efficiency and voltage, the resistances of lamps are inversely proportional to their candle-power, and the current and power increase directly with the candle-power.

Specific Resistance of Filaments. — The completed filament consists partly of the original cellulose or other material carbonized, and partly of the carbon deposited upon it when it is "flashed" or "treated." The specific resistance of the former differs greatly according to the material used, but is ordinarily between .0022 and .0035 ohms per cubic centimeter when hot, and about 1½ to 2 times greater when cold. The deposited carbon has a specific resistance about .12 to .16 as large as that of the untreated filament when both are hot, but the resistance of the former is increased about 2 to 2½ times at ordinary temperature. In almost all lamps the

proportion of the two kinds of carbon is such that the resistance of the treated filament is about twice as great when cold as when hot.

The variation in resistance is not great at or near the working temperature; in fact, most of the reduction in resistance occurs before the filament becomes red hot. This is fortunate, because a lamp is exceedingly sensitive to variations in voltage, and a decreased resistance with increased temperature would aggravate this difficulty. It would be desirable, in fact, to have the resistance of the filament increase with temperature, as in the case of metals, tending to keep the current constant if the voltage happens to rise or fall. Mr. J. W. Howell * has shown that this effect is obtained when the proportion of deposited carbon is large. This form of carbon is graphitic in character; and its resistance falls rapidly until the voltage is 30 or 40 per cent of its rated value, above which the resistance increases steadily even at 60 per cent excess over the normal voltage, which is the limit of the experiments, as the lamps burn out very quickly at this high temperature. The resistance of the untreated filament does not fall so rapidly at first as that of the deposited carbon, but it continues to diminish even when the voltage is raised to 60 per cent above the normal. Hence it is possible, by varying the proportion of original and deposited carbon, to have a positive, zero, or negative temperature coefficient at working voltage. In most cases it is practically zero. The original filament of Edison lamps has a specific resistance of 1.726 ohms per cubic mil cold, and .88 ohms at a temperature corresponding to 3.1 watts per c. p. The figures for the deposited carbon are .26 and .12 ohms respectively.

Size of Filaments. — The dimensions of a filament must fulfill two conditions: first, the resistance must be such that the lamp shall take the proper current and power at the voltage for which it is intended, as explained on p. 410; and second, the power lost by the filament as heat at the working temperature must exactly balance the electrical power supplied. The loss of heat from a body may take place in three ways: (1) by *conduction* through the bodies with which it is in contact; (2) by *convection* currents in the gas or liquid surrounding it; (3) by *radiation*. The filament of an incandescent lamp loses a small amount of heat by

* *Trans. Amer. Inst. Elec. Eng.*, vol. xiv., p. 30, 1897.

conduction through the leading-in wires; and since it is usually situated in a nearly perfect vacuum, it loses practically nothing by convection, hence the loss occurs almost entirely by radiation. The rate at which a body radiates heat is proportional to its surface, other things being equal, so that this surface must have a certain value for a given number of watts supplied. According to Newton's law of cooling, the loss of heat is also proportional to the elevation in temperature, and finally it depends upon the character or emissivity of the surface, that is, the number of heat units emitted from a unit surface per degree of temperature above that of the surrounding bodies. Above a red heat the illumination from the filament increases much more rapidly than the emission of heat, consequently the efficiency or candle-power per watt is greater the higher the temperature. There is a practical limit, however, to the temperature, above which the filament is too rapidly destroyed, so that there must be a compromise between the life of a lamp and its efficiency.

The actual working temperature of filaments is very difficult to measure. According to Prof. H. J. Weber it is 1591° C. at 3.1 watts and 1560° at 4 watts per candle-power. In practice this temperature is indirectly determined by the color of the light, the efficiency and the life of lamps, all of which depend upon it.

The filament may be rectangular in cross-section when cut out of cardboard or sheets of other material, and it has sometimes been made hollow; but ordinarily it is solid and circular, or slightly elliptical in section. In a filament having a diameter D and length L in centimeters, surface S in square cm., resistance when hot R_h, and carrying a current C, the heat produced must be proportional to the surface, since it is lost almost entirely by radiation. If H is this loss measured in watts per square cm., and r the specific resistance per cubic cm.

$$C^2 R_h = HS, \quad R_h = \frac{4\,Lr}{\pi D^2}, \quad \text{and} \quad S = \pi DL.$$

Hence by substitution

$$\frac{C^2\,4\,Lr}{\pi D^2} = H\pi DL, \quad \text{or} \quad D^3 = \frac{C^2\,4\,r}{H\pi^2}, \quad \text{and} \quad D = C^{\frac{2}{3}}\sqrt[3]{\frac{4r}{H\pi^2}}.$$

The quantity under the radical sign is constant for a given material at the working temperature, consequently D, the diame-

ter of the filament, must be made proportional to the $\frac{2}{3}$ power of the current. The length L disappears, hence for a given temperature (about the same for lamps using the same watts per candle-power) the diameter depends solely upon the current to be carried. The resistance R_h increases directly with the length L, hence $C R_h$, or the voltage required between the terminals of a filament, is directly proportional to its length, other things being equal. For example, a 220-volt lamp may be made by doubling the length of a 110-volt filament, a common plan being to use two of the latter in series. The current would be the same in both cases, hence the watts are twice as great for the 220-volt lamp, and the candle-power, being nearly proportional to the watts, would also be doubled. Two 16 candle-power filaments would give 32 candle-power; so in order to make a 16 candle-power, 220-volt lamp, it is necessary to reduce the diameter of the filament, making it the same as for 8 candle-power at 110 volts. Unfortunately the weakness, due to diminished diameter, requires the lamp to be run at a somewhat lower temperature, and therefore lower efficiency. For example, a 220-volt lamp may take 3.8 compared with 3.1 watts per candle-power for 110-volt lamps, or about 20% more power.

The actual sizes of filaments depend largely upon the proportion of deposited carbon, the specific resistance of the latter being about .12 to .16 that of the untreated filament, as already stated. Ordinarily the diameter is increased about 10 or 20% by the deposition of carbon.

Relations Between Voltage, Candle-Power, Efficiency, and Life. — The *voltage* of a lamp is the potential difference measured across its terminals. *Candle-power* may be defined in the various ways stated on page 308, the mean spherical candle-power being the complete measure, but the most difficult to determine. The mean horizontal candle-power may be easily measured, while the lamp is rotated 180 to 220 times per minute with its axis vertical, and it is that by which lamps are rated by their manufacturers; but the mean spherical is usually 15 to 20% less, as shown in the table on page 409. It has been recommended by the National Electric Light Association to measure the candle-power while the lamp is rotated with its axis inclined 45° to the photometer. This usually gives results approximating the mean spherical candle-power, but does not necessarily do so. In what follows, the mean

horizontal candle-power is used, since lamps are generally rated by it. The *efficiency* of a lamp is measured by the number of candle-power per watt. It is usually stated as the number of "watts per candle-power;" but of course this is the inverse of efficiency, since it is larger with poorer lamps. The *life* of a lamp means either the total number of hours it gives light before burning out, or the number of hours it burns, until its candle-power has fallen to a certain fraction — usually 80% of its rated value. The former might be called the *total*, and the latter the *useful* life, beyond which it is not economical, and should be replaced by a new lamp, even if it is capable of burning much longer. Unless otherwise stated, all data are given for lamps up to 125 volts, and are substantially true for 220 volts, but the latter are more sensitive.

The candle-power, etc., of lamps vary in much greater proportion than the voltage supplied, as shown in the following table:

VARIATION IN CANDLE-POWER, EFFICIENCY, AND LIFE.

In the following table is shown the variation in candle-power, efficiency, and useful life of General Electric standard 100 to 125 volt 3.1 and 3.5 watt lamps, due to variation of voltage supplied to them.

Per Cent of Normal Voltage.	Per Cent of Normal Candle-Power.	Efficiency in Watts Per Candle, 3.1-Watt Lamp.	Relative Life. 3.1-Watt Lamp.	Efficiency Watts Per Candle, 3.5 Watts.	Relative Life, 3.5 Watts.
90	53	4.65	9.41	5.36	
91	57	4.44	7.16	5.09	
92	61	4.24	5.55	4.85	
93	65	4.1	4.35	4.63	
94	69½	3.9	3.45	4.44	3.94
95	74	3.75	2.75	4.26	3.10
96	79	3.6	2.20	4.09	2.47
97	84	3.45	1.79	3.93	1.95
98	89	3.34	1.46	3.78	1.53
99	94½	3.22	1.21	3.64	1.26
100	100	3.1	1.000	3.5	1.00
101	106	2.99	.818	3.38	.84
102	112	2.9	.681	3.27	.68
103	118	2.8	.562	3.16	.58
104	124	2.7	.452	3.05	.47
105	130	2.62	.374	2.95	.39
106	137	2.54	.310	2.85	.31

For example, a lamp of 16 candle-power, 105 volts, and 3.1 watts, if burned at 103% of normal voltage, or about 108 volts,

will give 118 % of 16 candle-power, or 17.9 candle-power, the efficiency will be 2.8 watts per candle, but the life is reduced nearly one-half, being .562 of the normal.

In other words an increase of only 3 % in voltage raises the candle-power 18 %, the explanation being that up to a red heat no light is given, but after that increases rapidly with the temperature. Since the resistance of the filament is almost constant near the working temperature the current rises directly with the voltage, so that the watts for this case are 103 × 103 = 106 % of their normal value ; that is, 6 % more power produces 18 % more candle-power, the watts per candle-power being reduced from 3.1 to 2.8, an improvement of 10 %. Unfortunately this very desirable gain is offset by the decrease in life resulting from the higher temperature and the rapid falling off in candle-power and efficiency. Long experience has shown that filaments for 125 volts or less should be designed to run at a temperature that gives an efficiency of 3.1 to 3.5 watts per candle-power. Above this, the trouble and expense of renewing the lamps more than counterbalance the saving in power. It is also important to note that the rated watts per candle-power usually represent the *initial* efficiency and filaments that burn at too high temperature, soon show much poorer results, so that the *average* efficiency may not be improved. In the case of lamps for about 220 volts, it has not been found practicable to do better than 3.4 to 4 watts per candle-power (initial) owing to the greater length and smaller diameter of the filament as explained on p. 406.

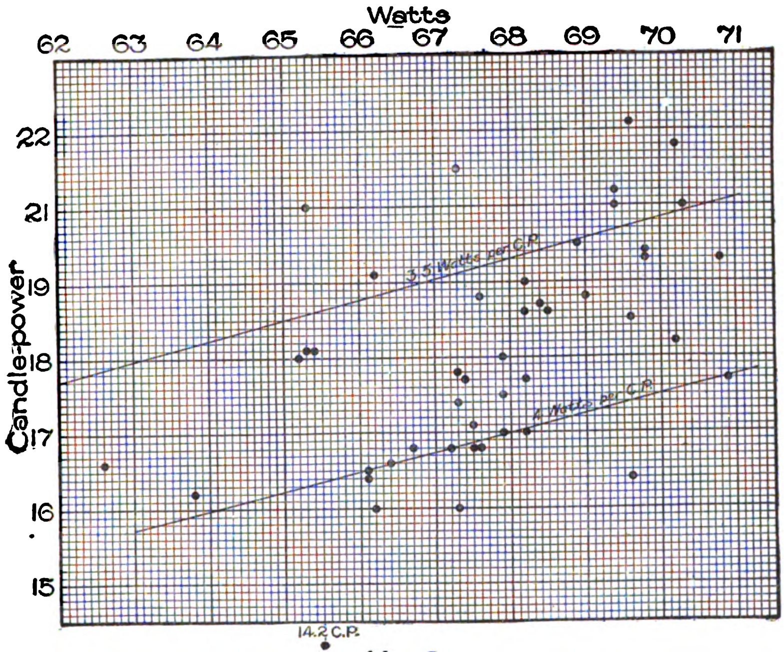
Another table, issued by the makers of the Packard lamp, is given below, showing results somewhat different from those on p. 414, the average life being less affected by raising or lowering the voltage. For example, 3.1 watt lamps having 580 hours average life at normal voltage, are stated to have a life of 280 hours at 6 % increased voltage. In the previous table the relative life is given at .31, that is, .31 × 580 = 179.8 hours, which is considerably less. The results of actual practice probably approximate more closely those contained in the former table. The *useful* life at normal or excessive voltage is actually less than here stated with the usual limit of 80 of the initial candle-power. For lives as long as those given in the table, the average candle-power would fall to 60 or 70 % of its initial value.

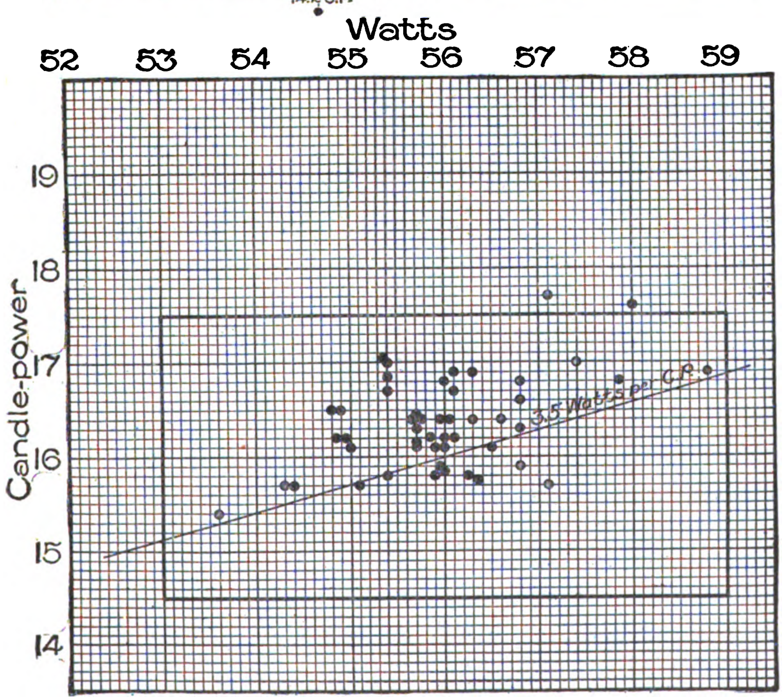
EFFICIENCY AND AVERAGE LIFE OF LAMPS AT VARIOUS VOLTAGES.

98 Per Cent of Normal Voltage.		100 Per Cent of Normal Voltage.		102 Per Cent of Normal Voltage.		104 Per Cent of Normal Voltage.		106 Per Cent of Normal Voltage.	
Actual Watts per C. P.	Actual Life in Hours.	Actual Watts per C. P.	Actual Life in Hours.	Actual Watts per C. P.	Actual Life in Hours.	Actual Watts per C. P.	Actual Life in Hours.	Actual Watts per C. P.	Actual Life in Hours.
4.85	3500	4.5	2400	4.21	1830	3.92	1400	3.7	1120
4.31	2000	4.	1500	3.74	1160	3.48	880	3.28	710
3.77	1200	3.5	900	3.27	700	3.05	550	2.87	440
3.34	760	3.1	580	2.9	460	2.7	360	2.54	280
2.69	350	2.5	260	2.34	210	2.18	170	2.05	140

Individual Performance of Lamps. The discrepancies just pointed out illustrate the great differences in rating and in results. This is partly due to different methods of manufacture and testing, and partly to wide variations in individual performance. The figures are supposed to represent averages ; but lamps, even when rated exactly the same, differ greatly from each other. The results of tests on a number of lamps are plotted upon what are called "target diagrams," as illustrated in Figs. 372 and 373. The former shows that the watts required to produce a given candle-power vary about 10%, and the candle-power runs from 16 to 21, with watts from 63 to 71, although the lamps were all supposed to be the same. These are bad results; but Fig. 373 is considered very satisfactory, since only 2 lamps out of 50 are outside of the limiting target, which permits 1.5 candle-power, and 3 watts range above or below the normal. The manufacturer attempts to hit the center, that is, obtain uniform results; and in this case has done fairly well with most of the lamps. Nevertheless, the individual differences are considerable, and show the difficulty of rating incandescent lamps exactly.

The Relation Between Candle-Power and Age in Fig. 374 also illustrates these differences, lamps of approximately equal initial candle-power giving from 11½ to 17½ candle-power at the end of 100 hours run. In some cases the candle-power rises at first, in others later, and in some not at all; but the general tendency is downward for all. The average shown by the dotted line is fairly good; being 14.1 candle-power, or 88 % of 16 candle-power at 600 hours, and apparently would fall to 80 % at about





Figs. 372, 373. Relation between Initial Candle-power and Watts Consumed.

850 hours, a satisfactory result for a 3.5 watt lamp. The decline in candle-power of an incandescent lamp, which continues until finally the filament burns out, is due to the following causes:

1. The filament wears away by evaporating or projecting particles of carbon from its surface.

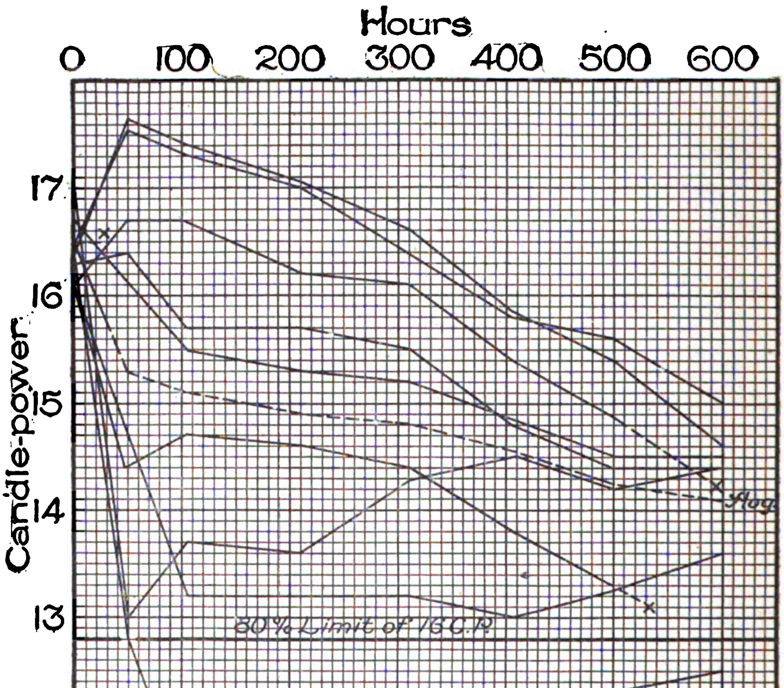


Fig. 374. Relation between Candle-power and Age.

2. The interior surface of the bulb becomes blackened and less transparent, owing to the carbon deposited upon it.

3. The emissivity (for heat) of the filament increases so that its temperature is lowered.

This falling candle-power is the most serious trouble with incandescent lamps, since it is not shown by a test in the beginning, and being so gradual escapes definite attention. It is, however, a common cause for dissatisfaction, producing the very

general impression that a so-called 16 candle-power incandescent lamp does not give as much light as the ordinary gas-burner (using 5 cu. feet per hour). This idea is well founded, because we have seen that lamps are rated by their mean horizontal candle-power, which is usually 15 to 20 % less than the mean spherical. Furthermore, the former falls to 80 % of its initial value at the end of the useful life, and the average is 90 %, assuming a uniform decline, which is close enough for practical purposes; so that the actual candle-power is about 25 % less than the nominal, or about 12 candle-power, compared with about 20 to 30 for the gas-burner.

This trouble is aggravated by the fact that lamps are rarely renewed when they have fallen 20% in candle-power, as the almost universal custom is to let them run until they burn out, which may take 1500 hours or more. During the latter half of this period, their average candle-power is often not more than 60 or 70 % of the initial candle-power; and the watts per candle-power have risen from 3.1 or 3.5 to 5 or 6, a loss of 30 or 40 % in actual light, and an increase in cost of 60 or 70 % per candle-power. The obvious conclusion is that it is uneconomical to burn lamps more than about 500 or 600 hours; and it would be a positive saving if one should break them at the end of this period; in fact, this limit has been aptly called the "smashing-point" * It is safe to say that hundreds of thousands of dollars are wasted annually in the world by not observing this important fact.

A further exaggeration of this bad situation arises from the common tendency to supply lamps with less than their normal voltage. A deficiency of at least 1 or 2 volts is the rule and not the exception, and it often amounts to 4 or 5 volts. This custom is the result of attempting to prolong the life of lamps as much as possible. It is, however, a "penny-wise and pound-foolish" practice, since the lamp itself costs about 20 cents, while the energy that it consumes costs $3.00 during a normal life of 400 hours at an ordinary price of .75 cent per 16 candle-power lamp-hour. A lamp using 3.1 watts per candle-power at normal voltage has an average life of 400 hours. If this lamp were burned at 98 % of normal voltage its life would be increased to 584 hours, but its

* *Electrica World*, Dec. 24, 1892. *Trans. Amer. Inst. Elec. Eng.*, vol. x., p. 65, 1893.

consumption of energy is raised to 3.34 watts per candle-power or 7.4 % more. At .75 cent per lamp-hour and for 584 hours' life the energy costs $4.38, on which an increase of 7.4% amounts to 32 cents. The lamp burns 584 − 400 = 184 hours longer, but this effects a saving of only (184 ÷ 400) × 20 = 9 cents, which is .28 as much as the extra cost of energy, the net loss being 32 − 9 = 23 cents. The sole advantage gained is the fact that the lamps are renewed every 548 instead of 400 hours, but this saving is only a small fraction of a cent per renewal.

This false economy is almost universal, because a man in charge of a lighting-plant notices each time that a lamp burns out, and considers it an actual loss of 20 cents. He forgets that in most cases the lamp has given light for 600 hours or more, and its cost *per hour of service* is only 20 ÷ 600 = .03 cent compared with .7 cent for energy. The importance of the latter item is only found by calculations based upon electrical and photometric tests, hence it is rarely appreciated by the ordinary user.

In the comparisons made above, the price of electrical energy has been taken at the rate charged by central stations, which varies from .5 to 1 cent per hour for a 16 candle-power lamp consuming 50 to 55 watts, an average rate being .75 cent. For isolated plants, in which the energy is generated on the spot, its cost may be only .15 to .25 cent per lamp-hour; but even then the extra energy required at 98% of normal voltage is one-fifth to one-third as much as before, or 32 ÷ 5 to 32 ÷ 3 = 6.4 to 10.7 cents for 584 hours, compared with a saving in lamps of 9 cents. Furthermore the price of lamps may be less than 20 cents. It is customary to regard the rated voltage of a lamp as a maximum value never to be exceeded, consequently the inevitable variations that occur produce an average at least 1 or 2 % below the normal pressure, and often it is 4 or 5 % too low, resulting in very poor economy. While it is injurious to run lamps above their normal voltage, nevertheless the *average* pressure should equal that for which they are rated, and the regulation (i.e., uniformity of voltage) should be good enough to avoid any serious shortening of life. Aside from any direct question of dollars and cents, the dissatisfaction and the depressing effect produced by running lamps beyond their normal life or below their rated pressure are sufficient reasons to demand very careful attention to this point.

Approximate Formulæ for Relations between Voltage, Efficiency, Life, and Candle-Power may be used within a limited range of about 5 % above or below the normal values, which is enough for any practical purpose. Calling V the voltage supplied at the lamp terminals, C the current in amperes, R its resistance (hot) in ohms assumed to be constant within the range named, W the power in watts consumed by it, D its candle-power, A the so-called efficiency in watts per candle-power, and L the normal life or average number of hours to reach 80 % of the rated candle-power, we have:

$$C = V \div R \ (1) \qquad R = V \div C \ (2) \qquad W = V^2 \div R = C^2 R \ (3)$$

$$C \propto V, \qquad \text{since } R \text{ is nearly constant,} \qquad (4)$$

$$W \propto V^2 \propto C^2, \qquad \text{" " " "} \qquad (5)$$

$$A \propto \frac{1}{V^4} \propto \frac{1}{C^4} \propto \frac{1}{W^2} \qquad \text{" " " "} \qquad (6)$$

$$D \propto V^6 \propto C^6 \propto W^3 \qquad \text{" " " "} \qquad (7)$$

$$L \propto \frac{1}{V^{20}} \propto \frac{1}{C^{20}} \propto \frac{1}{W^{10}}, \quad \text{Edison 3.1 Watt Lamps, p. 414,} \qquad (8)$$

To apply the above expressions, we may find R from (2) by measuring V and C with volt- and ampere-meters while a lamp is burning. From (4) we know that a certain increase or decrease in voltage, say 2 %, produces the same change in the current and (5) shows that the watts are proportional to the square of either voltage or current. From (6) we find that a lamp consuming 3.1 watts per candle-power, at rated voltage, requires at 98 % of that voltage $3.1 \div .98^4 = 3.1 \div .922^4 = 3.36$ watts per candle-power. This agrees closely with the value 3.34 given in the table on p. 414. From (7) its candle-power is found to be $.98^6 = .886$ of the normal compared with .89 in the table and from (9) its life is $1 \div .98^{20} = 1.5$ times normal compared with 1.46 in the table. These formulæ, as already stated, are merely approximate, and do not apply to individual lamps, but they bring out very important and interesting facts that are practically true when a number of results are averaged.

Special Lamps. — Almost innumerable varieties of lamps are made for different purposes. The standard voltages are 50 to 60, 100 to 120, and 200 to 240 for central station or isolated plant

lighting; but many others between and below these limits are also adopted. Prominent among these special types are the low-voltage lamps for use with storage or primary batteries, and ranging from 3 to 12 volts. In the larger sizes these are made like the standard lamps; but for the smaller sizes they are given special forms, as, for example, the bicycle lamp in Fig. 375, giving $\frac{3}{4}$ candle-power, and consuming .5 ampere at 4 volts. The surgical lamp, shown actual size in Fig. 376, represents one of the very smallest forms, requiring 3 volts and about 1 ampere, and giving $\frac{1}{2}$ candle-power.

Fig. 375. Bicycle Lamp.

Fig. 376. Surgical Lamp.

Another important class of low-voltage lamps includes the so-called series lamps. They are used in a candelabra or sign in order to subdivide the light and also simplify the wiring. They may be connected in series across an ordinary 110 volt or other constant potential circuit. It is necessary that the members of each series should be designed for the same current within .03 ampere. The lamps may differ in voltage, but the sum of the voltages in any series must equal that of the circuit within 3 volts. The lamp represented full size in Fig. 377 gives 1 candle-power, and consumes .33 ampere at 12.5 to 15 volts, being run 8 in series on 100 to 120 volts.

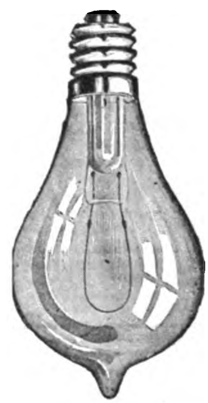


Fig. 377. Series Lamp.

Series lamps are also made for constant current circuits as described on pp. 24, 25, and in Chapter X. For a 10 ampere series arc circuit they require about $\frac{1}{3}$ volt per candle-power, and for the 3 or 3.5 ampere alternating or direct current circuits they use about 1 volt per candle-power; in either case the filaments are made sufficiently large to carry the current.

In addition to the many different voltages for which lamps are made, several different sizes are supplied for each voltage, the standards being 8, 16, 24, 32, 50, and 100 candle-power, but others are often required. Various shapes of lamps are manufactured for special purposes, as, for example, the tubular lamp in Fig. 369, and some ornamental forms. Finally lamps are made in many

colors, such as red, blue, green, amber, opal, frosted, etc., besides the ordinary clear glass bulbs. The result is that the total number of different styles of lamp that are made is many thousand.

Renewal of Filaments. — In most cases when a lamp burns out or is reduced in candle-power and efficiency below the economical limit, it is the filament alone that is worn out. The bulb, base, leading-in wires, etc., are usually intact and capable of being used again. The renewal of the filament and vacuum is now carried on successfully, the process being as follows: A hole is made in the bulb by removing the tip, and the carbonaceous deposit on the inner surface is burned off by the application of heat to the outside. The old filament is taken out through the aperture in the bulb and a new one introduced, being then connected to the leading-in wires by a pasted joint as described on p. 398. The joint is set, and the gases driven off by a blow-pipe inserted through the hole in the bulb. A tube similar to L M on p. 400 is attached to the bulb at the point where the hole was made, the parts being fused together, and the bulb is exhausted and hermetically sealed in the usual manner as described on p. 401. The brass base and the outer surface of the bulb are also cleaned if they require it, and the lamp then has the appearance and useful qualities of a new one.

The so-called *stopper-lamps* are easily renewable, since the inner part (A B in Fig. 349) that carries the filament fits into the bulb with a tapering ground joint similar to that of a glass stopper for a bottle. It is cemented in place in order to hold it and also make the seal more nearly air-tight. This type is more expensive to make than the ordinary lamp with fused joints, and does not maintain the vacuum so well.

"Turning Down" Incandescent Lamps. — It is often urged as an objection against these lamps that they cannot readily be made to give more or less light, as in the case of gas or oil lamps. In the majority of instances when the latter are turned down it is to save the trouble of relighting them, which does not apply at all to the incandescent lamp. Furthermore the light of the last-named may be diminished temporarily or permanently in several ways. One plan is to substitute a lower candle-power lamp in the same socket, which can easily be done in a few seconds. Another method is to insert resistance or, for alternating currents, inductance in the circuit. The resistance or inductance is placed in a

special socket and controlled by a key. A third arrangement employs two filaments which are connected in parallel or singly for full light and in series for reduced effect. A form of light is made in which a 16 and a 1 candle-power filament are put in the same bulb, and either may be lighted by turning the socket slightly. An obvious way to dim a light is to put a shade or a less translucent globe around it. This fails to save any energy when less illumination is required, but is simple and effective. A combustible shade, such as cloth, paper, or wood, should never be put in contact with or close around a lamp, as the heat will accumulate and may start a fire.

Specifications for Lamps.— In buying or making contracts for any considerable quantity of lamps it is customary to specify certain requirements.

The initial candle-power at the rated voltage should not be more than 9 % above or below the value called for. This margin amounts to 1½ candle-power for a 16 candle-power lamp, as shown in Fig. 373, the "target" (within which the lamps, must hit) extending from 14½ to 17½ candle-power. This limit applies to the *individual* performance of every lamp, and any that exceed it may be rejected. The *average* initial candle-power of a certain lot of lamps should be within 6 % of the rated value (1 candle-power for a 16 candle-power lamp). It is not desirable for lamps to be either above or below their rated candle-power, since their life is shortened in the former case, and their efficiency reduced in the latter, and either interferes with uniformity of results. The candle-power is usually measured when the lamp is mounted vertically in the photometer and rotated at about 180 r. p. m., the result being the mean horizontal candle-power. The relations between this and the mean spherical candle-power and candle-power from the tip are shown in Figs. 370–1. As already stated, the mean horizontal candle-power, being easily measured, and the one by which candle, oil, and gas lights are rated, is generally adopted. In some cases, it is specified that lamps shall not give less than 7 candle-power from the tip. The unit of light commonly accepted in this country is the British "Parliamentary Standard" candle-power. From this as a *primary* standard a number of incandescent lamps are carefully rated, and serve as excellent *secondary* standards, being burned only a minute or so at a time to check other incandescent lamps that are used as *working* standards.

Life of Lamps. — Since all of the above statements refer to *initial* candle-power, it is necessary to specify the *useful life* of a lamp, or the time it will burn before falling to a certain candle-power, usually 80 % of the initial candle-power. For lamps having an initial efficiency of 3.1 watts per candle-power, the useful life is about 400 to 450 hours. At 3.5 watts it is about 800, and at 4 watts about 1600 hours.

Candle-hours — The true measure of a lamp's value is the product of its useful life in hours and its average candle-power during that time. The latter is usually about 90 % of the initial, hence a 3.1 watt 16 candle-power lamp should give at least $400 \times 16 \times .90 = 5760$ candle-hours.

Efficiency. — The number of watts consumed per candle-power is another important point in lamp specifications. It refers usually to initial values, the specified useful life being a check upon the fall in candle-power and indirectly upon the efficiency. The standard efficiencies are 3.1, 3.5, and 4 watts per candle-power. Each lamp at rated voltage should take within 6 % of the watts specified, and the average for a large number should be within 4 % of the specified figure. If the efficiency is high (i.e., small consumption of power) the life is shortened, and vice versa, a fair compromise being adopted in practice, as explained on pp. 415 and 418. If the cost of energy is low, as for example in some water-power plants, a lower efficiency lamp may be used, but it is seldom economical to use 4 instead of 3.5 watt lamps. The useful life of the former is about 1600 hours compared with 800 for the latter, which would save one lamp costing about 20 cents every 1600 hours. The energy consumed in 1600 hours costs ½ to ¾ cent per lamp-hour at ordinary central station rates, or \$8 to \$12; and a 3.5-watt lamp would use one-eighth less energy than a 4-watt lamp, the saving being \$1 to \$1.50, which is 5 to 7½ times the cost of a lamp. Isolated electric-lighting plants in hotels, factories, etc., involve very little extra expense for engineers and other labor, or for coal when the exhaust steam is used for heating; hence the electrical energy may be produced at .15 to .25 cent per lamp-hour. For 1600 hours it amounts to \$2.40 to \$4.00, and one-eighth of this is 30 to 50 cents, which is also greater than the cost of a lamp, so that even then 4-watt lamps are less economical than those using 3.5-watts per candle-power. It may happen that

lamps are located in some inaccessible place, such as the ceiling of a large hall or railway station, and in that case it might be better to use the long-lived 4-watt lamps to save the trouble of frequent renewals. Where the regulation is poor (i.e., voltage varies considerably) the life is shortened, and it may be desirable to use 4-watt lamps.

Bulbs and Bases. — The former are specified to be uniform in size and of best quality glass, clean and free from flaws or blemishes. The metallic parts of the base should be of good quality brass, uniformly and accurately fitted to the bulb so as to be impervious to moisture. When placed in the socket no live metallic part (i.e., connected to the circuit) should be exposed.

Vacuum. — All lamps must have a practically perfect vacuum, and show no glow when tested with an induction coil giving a half-inch spark.

For further information regarding Incandescent Lamps, reference may be made to the following: —

The Incandescent Lamp and Its Manufacture, by Gilbert S. Ram, pp. 218, London, 1893.

A Life and Efficiency Test of Incandescent Lamps, by Professor B. F. Thomas and Messrs. Martin and Hassler, *Transactions of the American Institute of Electrical Engineers,* vol. ix., p. 271, 1892.

The Most Economical Age of Incandescent Lamps, by Carl Hering, *ibid.,* vol. x., p. 65, 1893.

Conductivity of Incandescent Carbon Filaments and of the Space Surrounding Them, by John W. Howell, *ibid.,* vol. xiv., p. 27, 1897.

The Incandescent Lamp (Manufacture), by Manning K. Eyre, *The Electrical World,* Jan. 5, 1895.

Incandescent Lamps, by Francis W. Willcox, *Journal of the Franklin Institute,* April, 1900.

CHAPTER XVIII.

LAMPS NOT EMPLOYING CARBON.

ALL forms of electric lamp in successful use prior to 1900 employed carbon as the light-giving body. This applies to arc lamps, which in all cases are provided with carbon electrodes, and to incandescent lamps, which employ carbon filaments. There are, however, two other interesting classes of lamps which do not use carbon: one includes the so-called *vacuum tubes*, in which all the light is emitted by a gas or vapor; and the other comprises incandescent lamps, in which the filament is composed of some material other than carbon, the *Nernst lamp* being a prominent example. The use of vacuum tubes as sources of light is a very old idea, being described by Hauksbee in a treatise published about two hundred years ago.* He employed glass vessels containing rarefied air, made luminous by frictional electricity, and to quote his own words, the light was "so great that large print, without much difficulty, could be read by it."

Similar, but not much more successful, attempts have been made repeatedly during the succeeding two centuries. The development of the Geissler and other improved forms of vacuum tube, and of the induction coil, during the past fifty years or more, has facilitated and encouraged such investigations.

Mr. Nikola Tesla, in a paper on "Experiments with Alternate Currents of Very High Frequency and Their Application to Methods of Artificial Illumination," † gave prominence to this subject, and has since investigated and written further in connection with it, but has not yet advanced beyond the experimental stage. A paper on "Recent Developments in Vacuum Tube Lighting," ‡ by Mr. D. McFarlan Moore, describes the methods

* *Physico mechanical Experiments, etc.*, London, 1709.

† *Transact. Amer. Inst. Elec. Eng.*, vol. viii., p. 267, May, 1891.

‡ *Ibid.*, vol. xiii., p. 85, April, 1896.

employed and results obtained by him. In his laboratory and at the New York Electrical Exhibition of 1896 he showed a room of considerable size lighted fairly well in this way, but no commercial applications have yet been made. In another series of investigations, Mr. Cooper Hewitt of New York City has succeeded in making a vacuum tube lamp of several hundred candle-power, and having a very high efficiency of about $\frac{1}{4}$ watt per candle-power; but these very promising results have not been published, and his methods up to the present time have not been applied commercially.

The chief advantages to be expected from vacuum tube lamps are high efficiency, long life, and distribution of light. The last is due to the large volume from which the light is given off; for example, a tube one foot long and an inch in diameter, or even larger, is luminous throughout. In the ordinary incandescent lamp the light is emitted from a filament six to ten inches long and a few thousandths of an inch in diameter. This is practically a line, and produces too sharp an image upon the retina, as shown by the fact that it persists after the eye is shut or turned away from the light.

The vacuum tube should have a long life, since the light-giving body being a gas, and not a solid, is not worn away. On the other hand, the degree of vacuum may rise or fall owing to absorption of the gas or leakage of air, in either case changing the resistance of the tube and interfering with constancy of action. The high efficiency of a vacuum tube results from the fact that a gas or vapor may be raised to a much higher temperature than a solid. The consequence is, the quantity of light emitted is increased in comparison with the emission of heat. In fact, such sources are often said to give "light without heat," but in most cases heat is given off with the light. Nevertheless, it is true that a glow-worm, for example, or some phosphorescent body, radiates a large part of its energy within the visible spectrum, the proportion of the longer, non-visible waves, called radiant heat, being far less than with ordinary sources of light.

There appears to be a discrepancy between the statements that the temperature in a vacuum tube is high, and yet the heat given off is small, but these are easily reconciled. If a 110-volt, 16 candle-power lamp is supplied with about 125 volts, it will give

32 candle-power. The power consumed is increased in about the ratio $110^2 : 125^2 = 12100 : 15625$, or about 30 per cent, as shown on page 421. Hence the rate of the total emission of energy is raised 30 per cent, but the light emitted is doubled. Thus the quantity of heat for the same amount of light would be only $130 \div 2 = 65$ per cent as great as before. By carrying this still further, the proportion of heat to light can be reduced very greatly, and what is called "light without heat" may be produced. It is also a fact that the temperature of the filament is increased at the same time, but in order to give the same candle-power its mass may be diminished. This applies exactly to a vacuum tube lamp in which the mass is very small, but the temperature of the individual particles is raised to a high point by the passage of electric current or discharge. It is possible that the electrical effect upon the atoms or ions may be somewhat different from what is ordinarily called high temperature; but it amounts to the same thing, since high rates of vibration or short wave lengths are produced.

In the experiments of Tesla, luminous discharges were created in vacuum tubes or even in the open air by a high frequency generator (10,000 to 20,000 periods per second) connected to the primary of an induction coil, the secondary of which gave very high voltage. He also employed a form of induction coil in the primary of which electrical oscillations are set up by sudden breaking of the circuit, producing a much higher frequency (100,000 or more periods per second), and therefore giving an extremely high voltage with only a few turns of wire. In this way vacuum tubes were made to glow by holding them near the terminals, but without any electrical connection to them. Such forms of apparatus are hardly suitable for practical use, and they involve considerable losses from leakage.

Moore employed induction tubes with connections made to them in the usual manner and operating at comparatively low voltage obtained from a self-induction coil with an electromagnetic make-and-break in the circuit. The latter was placed in a vacuum in order to give a sudden break and to avoid burning the contact points, but even with this precaution such a device is likely to give trouble. The Wehnheldt interrupter may be substituted, but it is doubtful if any form of break yet devised can be relied upon to act for the long periods of time demanded in lighting service.

The tubes developed by Hewitt are of sufficiently low resistance to operate at ordinary pressures. They may be connected directly to the present 110-volt circuits without requiring any step-up transformer or make-and-break device, which is a great advantage from the practical standpoint. Unfortunately it requires about 1000 volts to start the discharge, after which it is maintained by 110 volts.

The Nernst Lamp. — The type of lamp invented by Professor Nernst * of Göttingen, employs, in place of the long carbon filament of the ordinary incandescent lamp, a shorter "strip of material which is an insulator at ordinary temperatures, but becomes a good conductor and luminant at high temperatures." Usually it is composed of a mixture of metallic oxides, such as magnesia, yttria, zirconia, thoria, or ceria. Another feature of the Nernst lamp is the fact that the incandescent material is not burned by exposure to the air, consequently it need not be inclosed in a vacuum.

Since the filament does not become a conductor until heated, some means must be provided to raise its temperature so that the current may flow through it. Two methods are employed, one consisting simply in applying the flame of a match or alcohol lamp directly to the filament after it is connected to the circuit. When its temperature is raised sufficiently the current passes through it, bringing it up to and maintaining it at a white heat. The other method is automatic, the current being passed through a spiral *HH* which surrounds the filament *F* (Fig. 378), and heats it until the current flows through it.

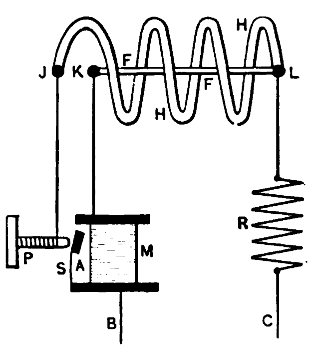


Fig. 378. Automatic Nernst Lamp.

This causes the magnet *M* in series with *F* to attract its armature *A* and break contact with the screw *P*, thus disconnecting the heating spiral *HH* which is in parallel with the filament *F*. When the lamp is turned out by opening the circuit, the spring *S* brings the armature *A* back into contact with the screw *P*, and the automatic device is ready to act again. The heating device *HH* is of porcelain, which, before being baked, is wound with a

* U. S. Patent No. 623,811, April 25, 1899.

great many turns of fine platinum wire. During the baking this wire becomes embedded in the porcelain, and is thus held firmly, only the outer surface being visible. The resistance R consists of iron wire placed in series with the filament F, so that the increase in resistance of the former compensates for the decreasing resistance of the latter, when the temperature rises.

The non-automatic lamp is provided with an open globe to permit lighting by a match; and the automatic form is contained in a closed globe, but it need not be air-tight. These lamps may be connected in parallel to the ordinary 110 or 220 volt circuits, and are claimed to have a high efficiency of 1.5 to 1.75 watts per candle-power, being one-half the power required by a carbon filament giving the same light. On the other hand the life is shorter, the average being about 200 to 300 hours, after which the filament loses its strength and increases in resistance. This, however, is the only part that is used up, and may be readily renewed, since the lamp is not hermetically sealed. The light is whiter than that of ordinary incandescent lamps, and the filament being much shorter, and giving 25, 50, or 100 candle-power, produces a dazzling effect on the eye unless a ground glass or equivalent globe is used. At the Paris Exposition of 1900 the Allgemeine Elektricitäts Gesellschaft of Berlin exhibited a room brilliantly illuminated by Nernst lamps, being the first important public application.

CHAPTER XIX.

METERS.

The general name meter may be applied to any device for measuring electrical quantities, and we have many forms of amperemeter, voltmeter, wattmeter, etc. Ordinarily, however, the term meter or electric meter, unless combined with another word, means an instrument to *record*, *register*, or *integrate* current in ampere-hours or energy in watt-hours. They are commonly used in stations or in the service connections of the various consumers to take account of the amount of current or energy supplied.

Classification of Meters. — Various electrical effects have been utilized in connection with meters, and the latter may be classified from that point of view, as follows:

Principle of action.	*Example.*
Electrochemical effects. . .	Edison meter.
Electrical heating effects. . .	Forbes meter.
Electromagnetic effects . .	American (Marks) meter.
Electrodynamic effects. . .	Thomson meter.
Alternating current effects .	Shallenberger meter.

Qualities Required in Meters. — Few devices are called upon to fulfill so many and such difficult conditions as those under which an electric meter is likely to work. For this reason its development has been one of the most serious problems that electrical engineers have had to solve. The chief qualities that are required or desired in meters are the following:

1. *Accuracy.* Under any reasonable conditions a meter should be at least commercially accurate, that is, its errors should not exceed 2 or 3 per cent.

2. *Range.* A meter should measure with commercial accuracy for any load from the maximum down to the smallest that may exist. This is probably the most difficult condition

to meet. For example, a meter that will record correctly for 100 lamps is not generally capable of acting at all when only one lamp is burning. Even if it takes some account of a single lamp, the record would be very inaccurate. To be sure, a certain percentage of error with a few lamps is less serious than for many, but it often happens that a small number may burn nearly all the time, in which case the aggregate error becomes large.

3. *Consumption of Energy.* Practically all forms of meter consume some energy, and if this loss goes on continually in a great many of them it may amount to a large item in the course of a year. Hence a meter should waste less than one per cent of the energy that it measures, and this loss should decrease somewhat in proportion to the load, which is usually the case.

4. *Drop in Voltage.* Besides the mere consumption of power, it is even more objectionable to have a drop in voltage on a constant potential system, especially for incandescent lighting. If the current C passes through any resistance R a drop C R is produced, hence the resistance introduced into the circuit by the meter should be as small as possible, so that the drop at full load shall not exceed $\frac{1}{4}$ per cent of the working voltage. In a wattmeter the series resistance produces such a drop as well as loss of energy, but the shunt coil merely uses a very small portion of the current, which is less objectionable.

5. *Durability.* It is very important that none of the parts should be likely to wear rapidly or get out of order.

6. *Attention.* The care and attention required should be small, and frequent inspection or testing unnecessary.

7. *Registration.* The meter should record or register in a clear manner, so that the consumer can read it at any time and check its accuracy.

8. *Testing.* It should be an easy matter to test the meter and verify it.

9. *Cheating.* The meter should be so constructed and protected that it is not liable to be tampered with in order to change its reading.

10. *Cost.* The price should be sufficiently low, so that a large deposit or rental need not be charged.

11. *Alternating and Direct Currents.* It is desirable that a meter may be used for either kind of current; but it is generally

bought for one or the other, and this point is not so very important.

12. *Frequency.* It is desirable also that variations in frequency should have no effect; but the latter being fixed in most cases, it is sufficient to adjust for it in the first place.

13. *Portability.* A meter should be strong enough so with moderate care it may be carried about without injury.

It cannot be expected that any meter will fulfill all of the above conditions, but there are several types in use which do so reasonably well.

Methods of Charging for Electrical Energy. — If the demand upon an electrical generating plant were uniform at all times, a simple charge of a certain rate per k. w. hour would be sufficient, possibly giving the larger consumers a lower rate, as is customary in other branches of business. In electric lighting, however, the demand varies widely at different hours of the day and night, which introduces serious difficulties in technical as well as business management. For example, the load between 5 and 6 P.M. in winter may be many times the average load. It is customary to call the ratio of the average load to the maximum the "load factor." This is often as low as 10 % and is rarely higher than 25 % in electric lighting. The use of energy for motors, heaters, etc., tends to make the demand more uniform, and therefore raises the load factor. It is evident that the capacity of machinery, etc., in an electric lighting plant must be somewhat greater than the maximum demand, in order to give a margin in case of breakdown of part of the apparatus. Hence an increase in the load at its maximum point requires a corresponding increase in capacity. On the other hand, the demand upon the system during hours in the day when the load is light can be taken care of without any increase in plant. In other words the station can afford to sell energy at a much lower rate during those hours. A striking illustration of the importance of this point is the fact that about one-quarter of the generating machinery in electric lighting stations is used only 50 to 100 hours per year, and may be practically idle during all the rest of the time. These hours are usually between 5 and 7 P.M. during December and January. It is quite evident that this machinery cannot possibly earn its interest and depreciation charge durings these few hours at ordi-

nary rates. It is necessary, however, to install it in order that the business may be held for the rest of the year. Various attempts have been made to take account of these points in charging for energy, and also to encourage its use at those hours when it can be delivered more economically. The several plans for selling electrical energy, some of which take account of these conditions, are as follows: —

METHODS OF CHARGING FOR ELECTRICAL ENERGY.

1st, *Contract* to supply a certain number of lamps at a fixed price per month, whether they are used or not.
2d, *Meter* with "flat" (i.e., uniform) rate.
3d, *Meter* taking account of *maximum demand.*
4th, *Meter, with two or more rates* of charge for different periods of the day.
5th, *Fixed charge* for energy *plus a graded charge* for the maximum capacity.
6th, *Prepayment meter,* which only allows energy to be delivered for a certain coin deposited.

The contract system of charging a fixed amount for a certain number of lamps was commonly adopted in the early days of electric lighting, except in Edison systems using the chemical meter. For street lighting, and other service requiring lights for a definite time, this system is satisfactory, but for residence lighting it is quite unsatisfactory, because the consumer is likely to burn the lamps for the full time when they are not needed. This wastes a large amount of energy, which must ultimately be paid for by the users. In such cases, and in fact for general use, some form of meter should be adopted. The common plan is to charge a certain price per lamp-hour or k. w. hour, which is graded according to the amount used. For example, a common practice is to charge one cent per lamp-hour, if the consumption is equivalent to the full number of lamps burning for one hour per day; $\frac{3}{4}$ cent if equivalent to two hours, and so on. This accomplishes its purpose fairly well, but fails, however, to take into account the particular time at which the lamps are burned. The latter point may be covered by using a two-rate meter, which separates the energy consumed during certain hours from that used during the rest of the time, a higher rate being charged for the former. One way of accomplishing this is to use two separate meters which are switched in or out of the circuit by clock-work. Another plan is to cause the meter to run faster during the time that a higher

charge is to be made, thus arriving at the same result. The prepayment meter is not intended to accomplish any of these ends, but is simply to avoid the necessity for giving credit.

The arbitrary method of charging a certain price per unit for one quantity, and ¾ as much for a greater quantity, is objectionable, because it leads to the absurd result that one may reduce the amount of his bill by using a little more current. The sliding-scale, in which the reduction is a certain percentage of the amount used, would avoid this difficulty. It might not be quite so easily understood as a certain price per lamp-hour, but customers would soon understand this plan. It would seem to be practically impossible to make a perfectly fair arrangement between producers and consumers; but a reasonable approximation can be reached, which is close enough for ordinary business purposes.

The Edison Chemical Meter was the first successful type, and many thousands of them were in regular and satisfactory service for a number of years. For reasons, given later, they have been replaced by other forms operating mechanically. In principle, this meter is based upon Faraday's law, according to which the amount of electrochemical action, for example, the weight of metal deposited or dissolved in an electrolytic cell, is directly proportional to the current, the chemical equivalent, and the time. The ampere, as legalized in all important countries, being defined in terms of the weight of silver deposited, this principle is fundamentally correct. For reasons of cheapness and as a result of numerous experiments, Edison adopted zinc as the best metal for the purpose.

The meter consists of a cell C, containing a solution of zinc sulphate having a density of 1.11, in which two zinc electrodes, A and B, are immersed. These are kept parallel and at a fixed distance apart by hard-rubber bolts. Connection is made to them by copper rods inserted in their upper ends, as indicated. In one of the main conductors, + or − which supply the lamps L, whose current is to be measured, a german-silver shunt S is introduced, having a certain resistance that is practically constant for ordinary temperature changes.

The electrolyte in the cell has a certain resistance, which decreases with rise of temperature; and in series with it is a coil R of copper wire whose resistance increases with temperature, the

two being proportioned so that they compensate each other and keep the resistance of the cell circuit almost perfectly constant for ordinary changes in temperature. The resistance of the coil R is about 4 times that of the bottle, and the two together have many times the resistance of the shunt S, so that a certain small fraction of the total current passes through the cell, dissolving zinc from the anode A and depositing it upon the cathode C. Once each month the electrodes are removed from the cell, being replaced by others, and the loss in weight of the anode is carefully weighed by a chemical balance. This loss in grams multiplied by the ratio of resistances of the two branches of the circuit and divided by .000337, the electrochemical equivalent of zinc, gives the total number of ampere-seconds during the month.

The possible sources of error are due to *temperature changes*, which are almost perfectly compensated in the cell circuit as already explained, and only vary the shunt S about $\frac{1}{2}$ per cent for 15°C above or below the normal. The cell has a certain *counter E.M.F.* of .001 to .003 volt, which introduces an error at loads less than 3 per cent of the maximum. *Oxidation* of the plates also occurs and is allowed for, otherwise the loss in weight would appear too low. The *drop* produced in the main circuit is small even at full load, being only about $\frac{1}{4}$ %.

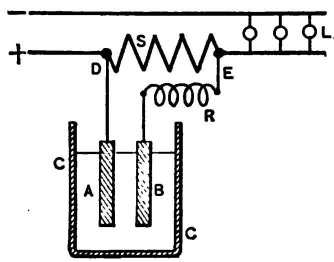


Fig. 379. Edison Chemical Meter.

With reasonable care this meter is fairly accurate; but the trouble of collecting and weighing the plates, and the fact that the consumer cannot read the record himself, has lead to the substitution of more convenient forms.

Thomson Recording Wattmeter.—This type, developed by Professor Elihu Thomson, and used in very large numbers in this country and abroad, is essentially an electric motor. The general appearance of the standard two-wire form for direct or alternating currents is shown in Fig. 380, and the connections in Fig. 381. The field magnet of the motor consists of two stationary coils of heavy wire directly in series with one of the main supply conductors, so that the entire current to be measured passes through them. An armature provided with a winding of many turns of

fine wire and having a resistance in series with it is connected across the circuit between the main conductors, and is mounted to rotate on a vertical axis between the two field coils. The armature is equipped with a miniature silver commutator and with brushes similar to those of a direct current motor, but, like the field coils, does not contain any iron core. Since the magnetic circuit passes through air and other non-magnetic materials, the flux through the armature, though small, is directly proportional to the main current. The armature circuit having a constant high

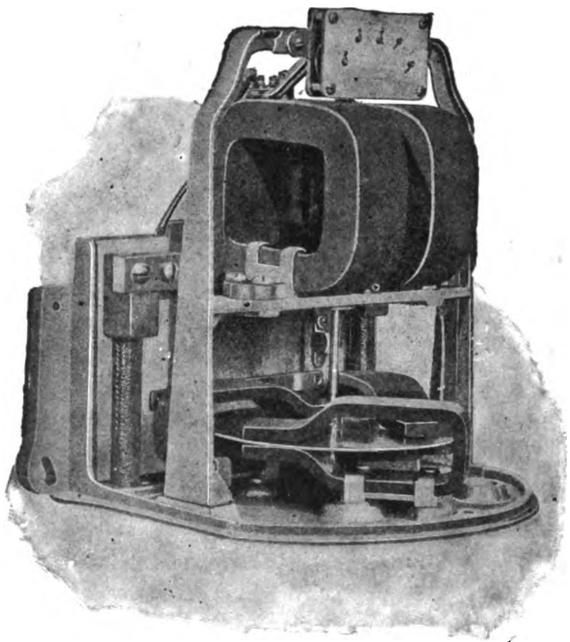


Fig. 380. Thomson Recording Wattmeter.

resistance connected across the two supply conductors, takes a current exactly proportional to the voltage between them. Hence the torque of the motor is in proportion to the product of these two currents or to the number of watts supplied at any instant. A copper disc mounted upon the shaft of the motor revolves between the poles of permanent magnets, as shown in Fig. 380, and acts as a brake, owing to the Foucault currents generated in it. These currents being directly proportional to the speed, the armature will rotate twice as fast with twice the

torque; consequently the revolutions per minute are directly proportional to the power supplied in watts. The total number of revolutions in any given time represents the energy in watt-hours. A train of wheels operates a series of five dials representing 1,111,100 units, usually watt-hours, and readings taken periodically show the energy consumed during the intervals.

It is evident that a motor meter requires a certain current to overcome friction, and would fail to record any current below this limit. In order to overcome this difficulty, an auxiliary field coil of fine wire marked "shunt" in Fig. 381 is put in series with the armature. Since the latter is connected across the main conductors, the current through it depends solely upon the voltage whether any lamps are burning or not. The resistance of the armature circuit is so adjusted that this current passing also through the shunt coil develops a torque almost sufficient to overcome friction; hence any current flowing in the main circuit and field coils will produce its full effect in rotating the armature. If the armature current is too strong it will cause slow rotation, even when no lamps are burning, and this "creeping" should be stopped by reducing the number of turns in the shunt field coil until the armature is not quite able to turn when no current for lighting or other purposes is being used.

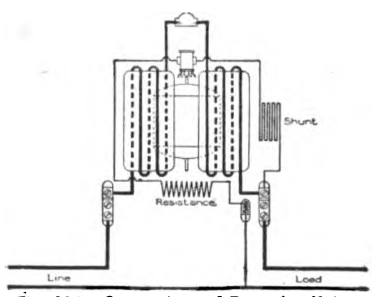


Fig. 381. Connections of Two-wire Meter.

The accuracy of the meter also requires that a certain number of watts supplied shall produce the proper number of revolutions per minute. Ordinarily 60 watts should cause the armature to rotate once per minute, and so on for other loads. Measuring the power with a wattmeter, or putting on a known load of lamps, enables the accuracy of the meter to be tested by counting the revolutions per minute. If found incorrect, the speed may be lowered by setting the permanent magnets farther out, or *vice versa*, an adjustment of about 16 % being possible. Since a reversal of current in both field and armature of a motor does not change the direction of rotation, an alternating current may be measured by this same instrument. The absence of iron cores

avoids any troubles from hysteresis or eddy current; but it is necessary that the reactance of the armature circuit should be very small compared with its resistance, a condition which is fulfilled by inserting resistance, as explained in relation to Fig. 381. A lag in the main current due to the load itself, as in the case of arc lamps or motors, does not introduce any error, since the instrument properly measures and integrates the true energy in watt-hours.

Special Forms of Thomson Meter are made for various purposes. The type whose connections are shown in Fig. 382 is designed for direct or alternating current three-wire circuits. In this case one main field coil is connected in series with each of the outer conductors, the armature circuit, including the shunt field, being connected between the neutral and one of the outer

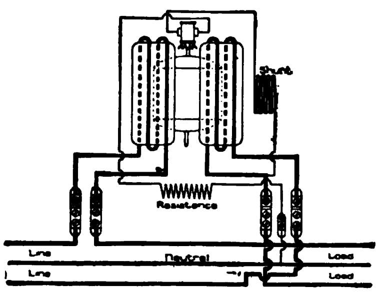


Fig. 382. Thomson Three-wire Meter.

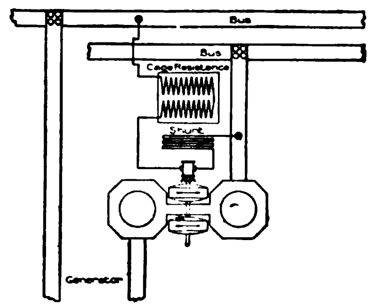


Fig. 383. Meter for Large Currents.

conductors, assuming that the two sides of the system are perfectly balanced. It may also be connected across both sides, thus measuring the total voltage; but the armature will then rotate twice as rapidly, for which fact adjustment or allowance should be made. The currents on either or both sides of the system produce their full effect in the main field coils.

The meters already described may be used for secondary or other low-voltage alternating circuits, but for primary or high-voltage circuits a modified form is applicable. The modification consists in inserting a small meter-transformer, which reduces the high voltage to a moderate value proportional to the original, the instrument being calibrated accordingly.

For measuring very large direct or alternating currents, as in generating plants, the field magnetism is produced by a single

bar of copper which passes between two armatures, as represented in 383, the arrangement in other respects being similar to that already described.

Two or three phase currents may be measured by means of a separate meter connected in each phase. If the energy of the two or three phases is kept balanced, one meter in one phase is sufficient, its readings being multiplied by two or three as the case may be. For unbalanced circuits the two or three separate instruments may be combined in one, as illustrated in Fig. 384.

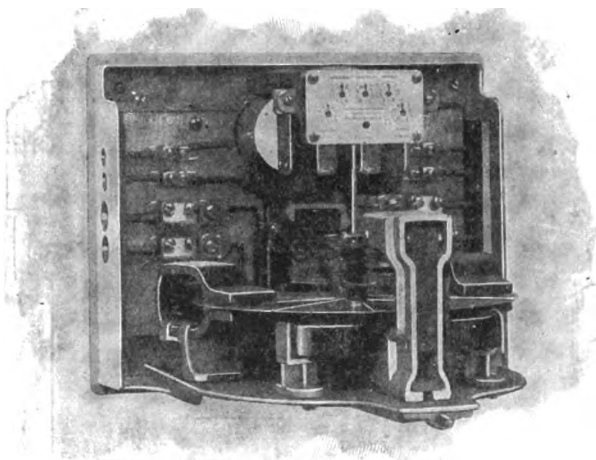


Fig. 384. Thomson Polyphase Meter.

A single instrument of this kind is capable of recording correctly the total load on balanced or unbalanced two-phase, three-phase, or monocyclic circuits, and saves space, expense, as well as the trouble of reading, and keeping account of two or more sets of dials. In many cases, however, separate meters are employed for the different phases of current. The arrangement for unbalanced three-phase or monocyclic circuits is shown in Fig. 385. One meter is connected to one branch of the circuit, and a second to another branch ; but none is required in the third branch, since no current can flow in it without passing through one or both of the other branches. The algebraic sum of the readings

of the two instruments gives the total power and is independent of the balance or lag of the currents. If the latter is less than 60°, giving a power factor greater than .50, the arithmetical sum of the readings is taken; but with a lag greater than 60°, the relation between the currents in the series and shunt coils of one

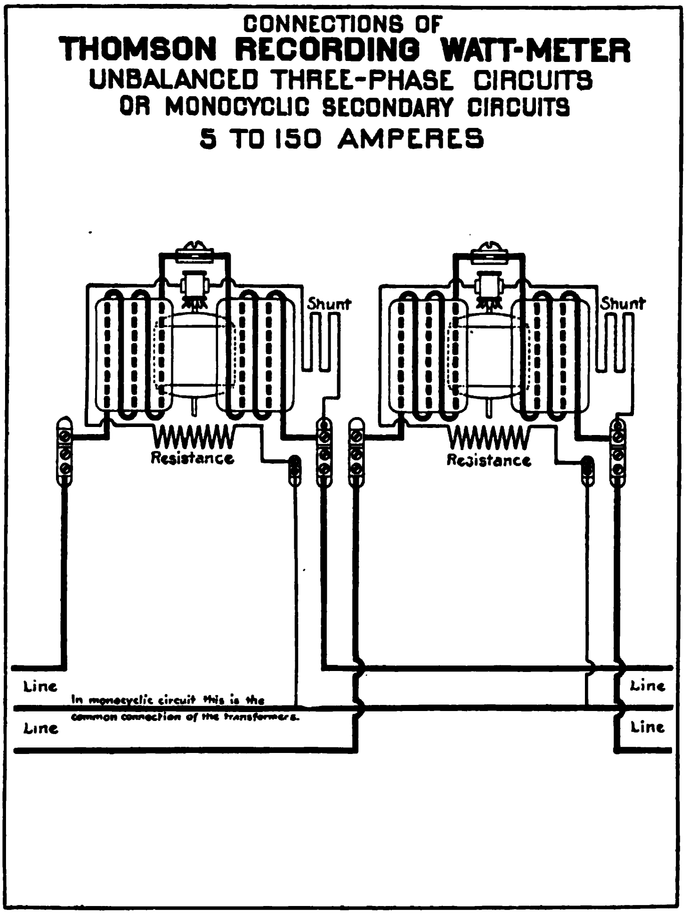


Fig. 385. Polyphase Circuit with Two Meters.

of the wattmeters causes it to have a negative reading, hence the difference between the two readings is equal to the actual power. In electric lighting the power factor is always greater than .50, and even with motors on the circuit it should be kept above that value. This arrangement is adapted to secondary or other low-voltage circuits; for primary or other high-voltage circuits, the

connections are similar, except that the pressure is reduced by meter-transformers as already explained.

For three-phase circuits with Y connection (p. 144), three separate meters may be used, one in each branch, but the single or the two-instrument arrangements are generally preferred.

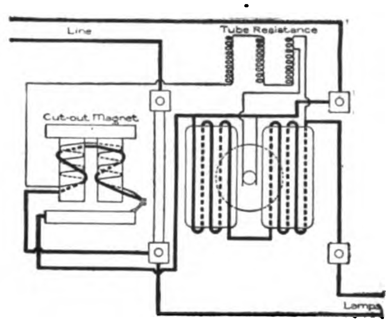


Fig. 386. Series Circuit Meter.

Series or Arc-Circuit Meter. — The Thomson instrument is adapted also to constant current circuits for series arc or incandescent lighting, the connections being represented in Fig. 386. The field coils of coarse wire are connected in series with one main conductor carrying the full current, the same as for constant potential circuits. In this case, however, a cut-out is provided which short-circuits the line at that point in case the circuit is opened beyond. The cut-out magnet is operated by coils in series with a high resistance and connected across the line wires. The armature is shunted across a portion of this resistance, as shown, and therefore receives a certain small fraction of the line voltage, so that with proper calibration the meter registers the watt-hours consumed in that portion of the circuit.

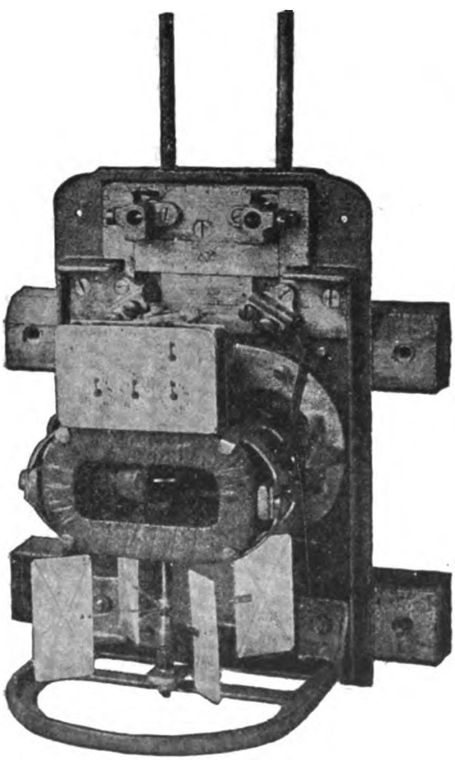


Fig. 387. Shallenberger Meter.

The Shallenberger Meter illustrated in Fig. 387 is a prominent form, having been made for many years by the Westinghouse

Company. It is of the motor type, but is applicable only to alternating currents and records ampere-hours but not watt-hours. It consists of large fixed coil having a few turns of heavy wire through which passes the entire current to be measured. Inside of this, and at an angle to it, is placed a closed copper coil. Within the latter a thin metallic disc is mounted to rotate upon a vertical spindle connected at its upper end with a train of recording gears and equipped below with four aluminium fan blades. When an alternating current passes through the large coil, it acts as a primary, and induces a current in the closed or secondary coil. The magnetic field produced by the secondary is at an angle to that of the primary, and the two combine to form a resultant field; but as their alternations do not coincide in time the direction of this resultant is continually shifting and produces a rotating field, as explained on page 145. The metallic disk tends to rotate in unison with the field, but is retarded by the fan blades. This device being in principle an induction motor, its torque increases as the square of the primary current; but since the resistance to rotation rises as the square of the speed (at moderate values), the number of revolutions per minute are directly proportional to the current, which is the condition required.

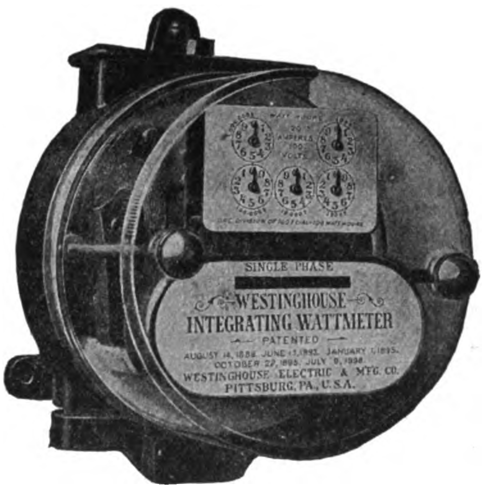


Fig. 388.

The Westinghouse Integrating Wattmeter (Fig. 388) is also of the induction motor type, but differs from the Shallenberger instrument, in having in addition to the series coils a shunt winding, the effect of which is proportional to the voltage, so that watt-hours are recorded. Since a rotating aluminium disk is acted upon by induction, it can be used only with alternating currents. The moving parts being very light require only 1.25 watts in the shunt winding, and even less in the series coils. The former advantage

is important because that loss occurs all the time, even when lamps are not burning, and any drop in the series coil is equally objectionable, since it reduces the pressure at the lamps. For 400 volts or less and currents up to 80 amperes, the meter is connected directly

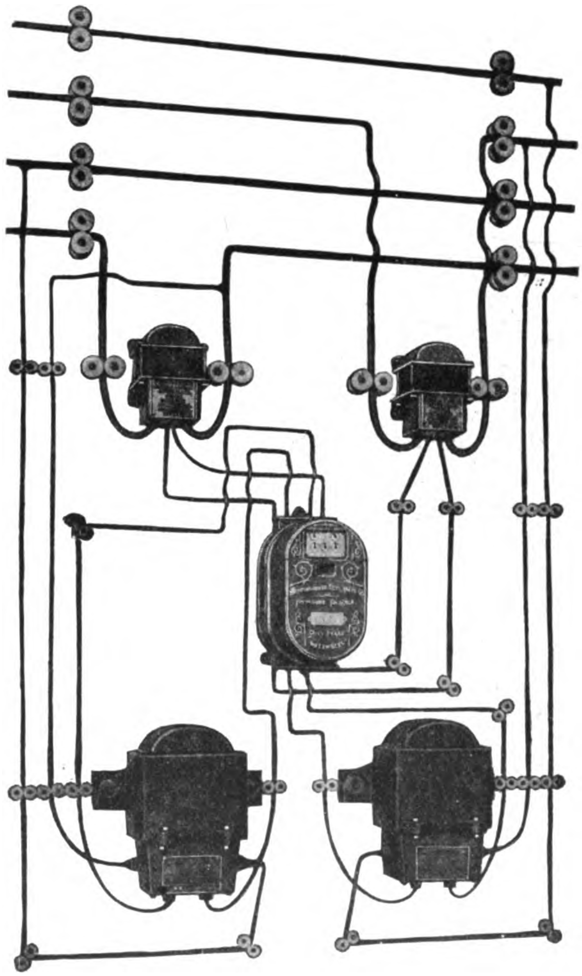


Fig. 389. Connections for Two-phase Westinghouse Meters.

to the circuit. With higher voltages or heavier currents a potential transformer is used to reduce the pressure for the shunt winding, and a series transformer is inserted in one of the main conductors to obtain a smaller but proportionate current for the series coil. The connections for a two-phase circuit are shown in Fig. 389, a

potential transformer for each phase being placed below and a smaller series transformer for each phase above, with all four secondary wires leading to a single meter in the center. The energy is brought from two-phase generators by four wires from the right, and after being measured is carried to the lamps by four wires on the left. The dials record the total energy supplied in all the branches of a polyphase circuit into which the wattmeter is connected, no multiplier being necessary.

The Duncan Integrating Wattmeter, represented in Fig. 390, is another well-known form of the induction motor type for alternating currents only. It comprises a series field core of laminated iron with inwardly projecting poles carrying the series coils, between which the armature — an inverted aluminium cup — rotates upon a vertical spindle, as shown. The shunt coil placed inside of the armature, with its axis at right angles to that of the series coils, is also wound upon a laminated iron core, being stationary and supported from below by a brass arm. The upper end of the armature spindle carries a gear driving the train of dials, and on the lower end is mounted the retarding disk of aluminium which revolves between the poles of two permanent magnets. The so-called compensator is a copper ring with an iron core shown in front of the armature and supported by a movable arm. By adjusting its position, friction may be overcome and at the same time "creeping" avoided. The lower bearing of the spindle is of sapphire and the spindle point of hardened steel, both of which are easily renewable.

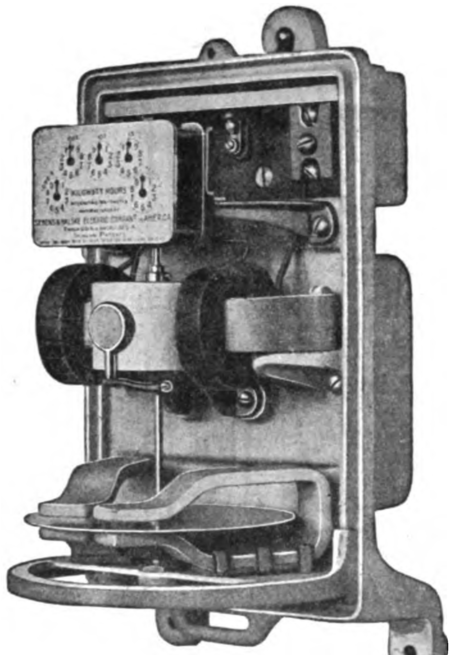


Fig. 390. Duncan Meter.

The Gutmann Integrating Wattmeter is similar in principle to the Westinghouse and Duncan instruments, being of the induction motor type with series and shunt windings, and is adapted only to alternating currents. The arrangement of the dials, retarding disk and other parts is also similar, but the armature or rotating member is a diagonally slotted aluminium cylinder.

The American Integrating Amperemeter, illustrated in Fig. 391, differs radically from those already described, both in principle and in construction. It consists of a solenoid and core placed above a self-starting pendulum, actuated by the electric current. The pendulum, by means of a cam, raises a pawl on a ratchet

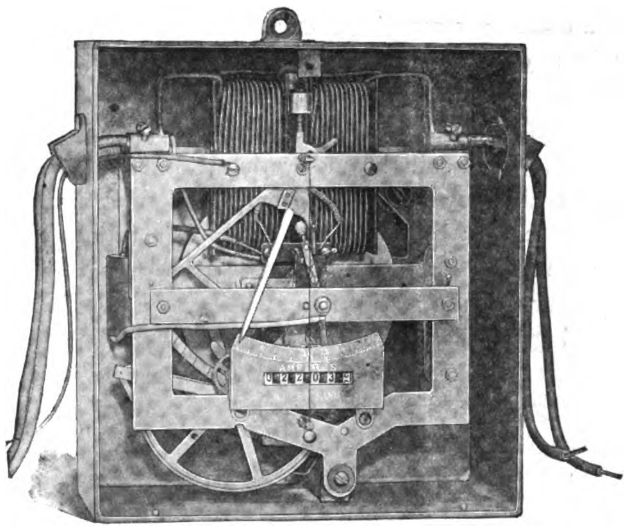


Fig. 391. The American Integrating Amperemeter.

wheel to a uniform height each stroke. The solenoid, by means of its core, shifts the angular position of a pendent arch attached to its axis so as to permit this pawl to drop along the ratchet wheel a number of teeth proportional to the current passing through the meter; thus at each stroke of the pendulum the load in amperes passing to the consumer is, by means of the ratchet wheel and the counter register, measured and added up in ampere-hours.

The pendulum ceases to swing when no lamps are burning; but as soon as any are turned on, and current flows in the main conductor, the pendulum is started automatically, being actuated by a

shunt circuit across the mains. The form illustrated is for use on a three-wire system, both of the outer conductors being carried through the solenoid, as indicated, so that its action upon the core, and therefore the position of the latter, depends upon the combined effects of the two currents, thus measuring the total load on both sides of the system. The core of soft iron is magnetized to saturation by a winding in circuit with the coil that drives the pendulum, the object being to avoid variations due to hysteresis. Having this construction, the instrument measures ampere-hours simply, since ordinary changes in voltage would produce no appreciable effect.

The Ferranti Meter used in England is based upon the principle that a conductor carrying a current in a magnetic field tends to move in a direction perpendicular to the current and to the lines of force. In this case the conductor consists of mercury contained in a shallow circular chamber placed between the poles of a magnet excited by a coil through which the main current passes. This current also flows radially through the mercury being introduced at the center by a pin, and taken off at the periphery by a metallic rim. The retarding force is that due to fluid friction of the mercury against the inner surface of the chamber, in which radial grooves are formed to increase the effect and make it as nearly as possible proportional to the square of the speed. Since the current flows in both the magnet and the mercury, the driving force is proportional to the square of the current, and the speed, therefore, increases directly with the current. A vane dipping in the mercury transmits the motion of the latter to the counting dials by means of a small spindle. The driving force due to residual magnetism is designed to overcome the retarding force due to the solid friction of the parts. It is evident that this instrument measures ampere-hours and not watt-hours.

The Aron Meter consisted originally of an ordinary clock having a permanent magnet for the bob of the pendulum, below which was placed a coil with its axis vertical. The current to be measured passed through the coil in the direction to repell the magnet, thus neutralizing a part of its gravity which caused the clock to lose time. The loss of time in any period enabled the ampere-hours during that period to be determined. A later form comprised two separate clocks, one acting normally and the other

being influenced by the current. The two trains of wheels were connected by a differential gear to a third train with dials and pointers which indicated the difference in action of the two clocks, being calibrated in ampere-hours. This type involves two obvious difficulties: one is the trouble of winding the clocks, and the other is the practical impossibility of keeping correct a large number of clocks of reasonable cost. These objections are overcome in a still more recent form which is made self-winding by the action of the current, and each pendulum is acted upon by a coil so that one is accelerated and the other retarded, thus doubling the effect. Furthermore, at frequent intervals the connections of the coils are reversed, so that first one and then the other pendulum is the faster, the *difference* between the two being always registered on the dials. In this way even a considerable deviation from accuracy in one or both of the clocks is eliminated by the constant reversal of their relations. Another feature in the improved Aron instrument is the substitution of a shunt coil for the permanent magnet on each pendulum, thus converting it into an integrating wattmeter. It is adapted to either direct or alternating currents, and is made in forms suitable for two-wire, three-wire, and other circuits.

The Terms Integrating, Recording, and Registering Meter are all used for designating the various devices described in this chapter. The first is certainly correct, since in most cases the instrument merely integrates or sums up the total number of ampere- or watt-hours, without making any record of the almost constant variations in load which usually occur. There are also instruments commonly called recording volt-, ampere-, or wattmeters, in which a line is traced out on paper showing the number of volts, etc., at any time during the entire twenty-four hours. By using an ampere- or wattmeter of this kind and properly integrating the record obtained, the number of ampere- or watt-hours may be determined. This is much less convenient, however, than an instrument which automatically performs the integration and gives the result on a dial. On the other hand, the maximum demand and other values would all be shown, so that a charge could be made taking them into account, as explained in the beginning of this chapter. As a matter of fact, such instruments are rarely used except to ascertain the uniformity of voltage, etc., when it is desired to have it con-

stant, and are used merely as a check on the regulation. It has been proposed to distinguish between this class and those which integrate, by calling the former recording and the latter registering; but common usage is the other way, and the term integrating meter is more distinctive for the latter. In most cases the simple word "meter" is understood to mean the integrating instrument, whether used for measuring gas, water, or electrical quantities.

APPENDIX I.

"NATIONAL ELECTRICAL CODE"

RULES AND REQUIREMENTS

OF THE

NATIONAL BOARD OF FIRE UNDERWRITERS

FOR THE INSTALLATION OF

WIRING AND APPARATUS

FOR ELECTRIC LIGHT, HEAT, AND POWER

AS RECOMMENDED BY THE

UNDERWRITERS' NATIONAL ELECTRIC ASSOCIATION

EDITION OF 1901

The National Electrical Code, as it is here presented, is the result of the united efforts of the various Electrical, Insurance, Architectural, and allied interests which have, through the National Conference on Standard Electrical Rules, composed of delegates from various National Associations, unanimously voted to recommend it to their respective Associations for approval or adoption.

The following is a list of the Associations represented in the Conference, all of which have approved of the Code:

American Institute of Architects
American Institute of Electrical Engineers
American Society of Mechanical Engineers
American Street Railway Association
Factory Mutual Fire Insurance Companies
National Association of Fire Engineers
National Board of Fire Underwriters
National Electric Light Association
Underwriters' National Electric Association

GENERAL PLAN GOVERNING THE ARRANGEMENT OF RULES

CLASS A.—**Central Stations, Dynamo, Motor, and Storage-Battery Rooms, Transformer Substations, etc.** Rules 1 to 11.

CLASS B.—**Outside Work,** all systems and voltages. Rules 12 and 13.

CLASS C.—**Inside Work.** Rules 14 to 39. Subdivided as follows:
General Rules, applying to all systems and voltages. Rules 14 to 17.
Constant-Current systems. Rules 18 to 20.
Constant-Potential systems.
All voltages. Rules 21 to 23.
Voltage not over 550. Rules 24 to 31.
Voltage between 550 and 3,500. Rules 32 to 37.
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CLASS D.—**Specifications for Wires and Fittings.** Rules 40 to 63.

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CLASS F.—**Marine Wiring.** Rules 68 to 80.

CLASS A

STATIONS AND DYNAMO ROOMS

INCLUDES CENTRAL STATIONS, DYNAMO, MOTOR, AND STORAGE-BATTERY ROOMS, TRANSFORMER SUBSTATIONS, ETC.

1. **Generators**—

a. Must be located in a dry place.

b. Must never be placed in a room where any hazardous process is carried on, nor in places where they would be exposed to inflammable gases or flyings of combustible materials.

c. Must be insulated on floors or base frames, which must be kept filled to prevent absorption of moisture, and also kept clean and dry. Where frame insulation is impracticable, the Inspection Department having jurisdiction may, in writing, permit its omission, in which case the frame must be permanently and effectively grounded.

A high-potential machine which, on account of great weight or for other reasons, cannot have its frame insulated from the ground, should be surrounded with an insulated platform. This may be made of wood, mounted on insulating supports, and so arranged that a man must always stand upon it in order to touch any part of the machine.

In case of a machine having an insulated frame, if there is trouble from static electricity due to belt friction, it should be overcome by placing near the belt a metallic comb connected with the earth, or by grounding the frame through a very high resistance of not less than 200 ohms per volt generated by the machine.

d. Every constant-potential generator must be protected from excessive current by a safety fuse, or equivalent device, of approved design in each lead wire.

These devices should be placed on the machine or as near it as possible.

Where the needs of the service make these devices impracticable, the Inspection Department having jurisdiction may, in writing, modify the requirements.

e. Must each be provided with a waterproof cover.

f. Must each be provided with a name-plate, giving the maker's name, the capacity in volts and amperes, and the normal speed in revolutions per minute.

2. **Conductors**—

From generators to switchboards, rheostats, or other instruments, and thence to outside lines.

a. Must be in plain sight or readily accessible.

b. Must have an *approved* insulating covering as called for by rules in Class "C" for similar work, except that in central stations, on exposed circuits, the wire which is used must have a heavy braided non-combustible outer covering.

Bus bars may be made of bare metal.

c. Must be kept so rigidly in place that they cannot come in contact.

d. Must in all other respects be installed under the same precautions as required by rules in Class "C" for wires carrying a current of the same volume and potential.

3. **Switchboards** —

a. Must be so placed as to reduce to a minimum the danger of communicating fire to adjacent combustible material.

Special attention is called to the fact that switchboards should not be built down to the floor, nor up to the ceiling, but a space of at least ten or twelve inches should be left between the floor and the board, and from eighteen to twenty-four inches between the ceiling and the board in order to prevent fire from communicating from the switchboard to the floor or ceiling, and also to prevent the forming of a partially concealed space very liable to be used for storage of rubbish and oily waste.

b. Must be made of non-combustible material or of hardwood in skeleton form filled to prevent absorption of moisture.

c. Must be accessible from all sides when the connections are on the back, but may be placed against a brick or stone wall when the wiring is entirely on the face.

d. Must be kept free from moisture.

e. Bus bars must be equipped in accordance with rules for placing conductors.

4. **Resistance Boxes and Equalizers** —

(*For construction rules, see No. 60.*)

a. Must be placed on a switchboard or, if not thereon, at a distance of a a foot from combustible material, or separated therefrom by a non-inflammable, non-absorptive, insulating material.

5. **Lightning Arresters** —

(*For construction rules, see No. 63.*)

a. Must be attached to each side of every overhead circuit connected with the station.

It is recommended to all electric light and power companies that arresters be connected at intervals over systems in such numbers and so located as to prevent ordinary discharges entering (over the wires) buildings connected to the lines.

b. Must be located in readily accessible places away from combustible materials, and as near as practicable to the point where the wires enter the building.

Station arresters should generally be placed in plain sight on the switchboard.

In all cases, kinks, coils, and sharp bends in the wires between the arresters and the outdoor lines must be avoided as far as possible.

c. Must be connected with a thoroughly good and permanent ground connection by metallic strips or wires having a conductivity not less than that of a No. 6 B. & S. copper wire, which must be run as nearly in a straight line as possible from the arresters to the earth connection.

Ground wires for lightning arresters must not be attached to gas-pipes within the buildings.

It is often desirable to introduce a choke coil in circuit between the arresters and the dynamo. In no case should the ground wire from a lightning arrester be put into iron pipes, as these would tend to impede the discharge.

6. Care and Attendance —

a. A competent man must be kept on duty where generators are operating.

b. Oily waste must be kept in *approved* metal cans and removed daily.

Approved waste cans shall be made of metal, with legs raising can three inches from the floor, and with self-closing covers.

7. Testing of Insulation Resistance —

a. All circuits, except such as are permanently grounded in accordance with Rule 13 A, must be provided with reliable ground detectors. Detectors which indicate continuously, and give an instant and permanent indication of a ground, are preferable. Ground wires from detectors must not be attached to gas-pipes within the building.

b. Where continuously indicating detectors are not feasible, the circuits should be tested at least once per day, and preferably oftener.

c. Data obtained from all tests must be preserved for examination by the Inspection Department having jurisdiction.

These rules on testing to be applied at such places as may be designated by the Inspection Department having jurisdiction.

8. Motors —

a. Must be insulated on floors or base frames, which must be kept filled to prevent absorption of moisture; and must be kept clean and dry. Where frame insulation is impracticable the Inspection Department having jurisdiction may, in writing, permit its omission, in which case the frame must be permanently and effectively grounded.

A high-potential machine which, on account of great weight or for other reasons, cannot have its frame insulated, should be surrounded with an insulated platform. This may be made of wood mounted on insulating supports, and so arranged that a man must stand upon it in order to touch any part of the machine.

In case of a machine having an insulated frame, if there is trouble from static electricity due to belt friction, it should be overcome by placing near the belt a metallic comb connected to the earth, or by grounding the frame through a very high resistance of not less than 200 ohms per volt generated by the machine.

b. Must be wired under the same precautions as required by rules in class "C", for wires carrying a current of the same volume and potential.

The leads or branch circuits should be designed to carry a current at least fifty per cent greater than that required by the rated capacity of the motor to provide for the inevitable overloading of the motor at times without overfusing the wires.

c. The motor and resistance box must be protected by a cutout and controlled by a switch (see No. 17 *a*), said switch plainly indicating whether "on" or "off" Where one-fourth horse-power or less is used on low-tension circuits

a single-pole switch will be accepted. The switch and rheostat must be located within sight of the motor, except in such cases where special permission to locate them elsewhere is given in writing by the Inspection Department having jurisdiction.

d. Must have their rheostats or starting-boxes located as to conform to the requirements of No. 4.

In connection with motors the use of circuit-breakers, automatic starting-boxes and automatic under-load switches is recommended, and they *must* be used when required.

e. Must not be run in series-multiple or multiple-series, except on constant-potential systems, and then only by special permission of the Inspection Department having jurisdiction.

f. Must be covered with a waterproof cover when not in use, and, if deemed necessary by the Inspection Department having jurisdiction, must be inclosed in an approved case.

From the nature of the question the decision as to what is an approved case must be left to the Inspection Department having jurisdiction to determine in each instance.

g Must, when combined with ceiling fans, be hung from insulated hooks, or else there must be an insulator interposed between the motor and its support.

h. Must each be provided with a name-plate, giving the maker's name, the capacity in volts and amperes, and the normal speed in revolutions per minute.

9. Railway Power Plants —

a. Must be equipped in each feed wire before it leaves the station with an *approved* automatic circuit-breaker (see No. 52) or other device, which will immediately cut off the current in case of an accidental ground. This device must be mounted on a fireproof base, and in full view and reach of the attendant.

10. Storage or Primary Batteries —

a. When current for light and power is taken from primary or secondary batteries, the same general regulations must be observed as applied to similar apparatus fed from dynamo generators developing the same difference of potential.

b. Storage battery rooms must be thoroughly ventilated.

c. Special attention is directed to the rules for rooms where acid fumes exist (see No. 24, *j* and *k*).

d. All secondary batteries must be mounted on non-absorptive, non-combustible insulators, such as glass or thoroughly vitrified and glazed porcelain.

e. The use of any metal liable to corrosion must be avoided in cell connections of secondary batteries.

11. Transformers —

(*For construction rules, see No. 62.*)

a. In central or substations the transformers must be so placed that smoke from the burning out of the coils or the boiling over of the oil (where oil-filled cases are used) could do no harm.

CLASS B.

OUTSIDE WORK.

ALL SYSTEMS AND VOLTAGES.

12. **Wires**—

a. Service wires must have an *approved* rubber insulating covering (see No. 41). Line wires, other than services, must have an *approved* weatherproof, or rubber insulating covering (Nos. 41 and 44). All the wires must have an insulation equal to that of the conductors they confine.

b. Must be so placed that moisture cannot form a cross connection between them, not less than a foot apart, and not in contact with any substance other than their insulating supports. Service blocks must be covered over their entire surface with at least two coats of waterproof paint.

c. Must be at least seven feet above the highest point of flat roofs, and at least one foot above the ridge of pitched roofs over which they pass or to which they are attached.

d. Must be protected by dead insulated guard iron or wires from possibility of contact with other conducting wires or substances to which current may leak. Special precautions of this kind must be taken where sharp angles occur, or where any wires might possibly come in contact with electric light or power wires.

e. Must be provided with petticoat insulators of glass or porcelain. Porcelain knobs or cleats and rubber hooks will not be approved.

f. Must be so spliced or joined as to be both mechanically and electrically secure without solder. The joints must then be soldered, to insure preservation, and covered with an insulation equal to that on the conductors.

All joints must be soldered, even if made with some form of patent splicing device. This ruling applies to joints and splices in all classes of wiring covered by these rules.

g. Must, where they enter buildings, have drip loops outside, and the holes through which the conductors must be bushed with non-combustible, non-absorptive insulating tubes slanting upward toward the inside.

h. Telegraph, telephone, and similar wires must not be placed on the same cross-arm with electric light or power wires; and when placed on the same pole with such wires the distance between the two inside pins of each cross-arm must not be less than twenty-six inches.

i. The metallic sheaths to cables must be permanently and effectively connected to "earth."

TROLLEY WIRES.

j. Must not be smaller than No. 0 B. & S. copper or No. 4 B. & S. silicon bronze, and must readily stand the strain put upon them when in use.

k. Must have a double insulation from the ground. In wooden-pole construction the pole will be considered as one insulation.

l. Must be capable of being disconnected at the power plant, or of being divided into sections, so that, in case of fire on the railway route, the current may be shut off from the particular section and not interfere with the work of the firemen. This rule also applies to feeders.

m. Must be safely protected against accidental contact where crossed by other conductors.

Guard wires should be insulated from the ground, and should be electrically disconnected in sections of not more than 300 feet in length.

GROUND RETURN WIRES.

n. For the diminution of electrolytic corrosion of underground metal work, ground return wires must be so arranged that the difference of potential between the grounded dynamo terminal and any point on the return circuit will not exceed twenty-five volts.

It is suggested that the positive pole of the dynamo be connected to the trolley line, and that whenever pipes or other underground metal work are found to be electrically positive to the rails or surrounding earth, that they be connected by conductors arranged so as to prevent as far as possible current flow from the pipes into the ground.

13. **Transformers —**

(*For construction rules, see No. 62.*)

a. Must not be placed inside of any building, excepting central stations, unless by special permission of the Inspection Department having jurisdiction.

b. Must not be attached to the outside walls of buildings, unless separated therefrom by substantial supports.

13 A. **Grounding Low Potential Circuits.**

The grounding of low potential circuits under the following regulations is only allowed when so arranged that under normal conditions there will be no flow of current through the ground wire.

Direct Current 3-Wire Systems.

a. Neutral wire may be grounded, and when grounded the following rules must be complied with: —

1. Must be grounded at the Central Station on a metal plate buried in coke beneath permanent moisture level, and also through all available underground water and gas-pipe systems.

2. In underground systems the neutral wire must also be grounded at each distributing-box through the box.

3. In overhead systems the neutral wire must be grounded every 500 feet, as provided in Sections *c*, *e*, and *f*.

The Inspection Department having jurisdiction may require grounding if they deem it necessary.
Two-wire direct current systems having no accessible neutral point are not to be grounded.

Alternating Current Secondary Systems.

b. The neutral point of transformers, or the neutral wire of distributing systems, may be grounded, and when grounded the following rules must be complied with: —

1. Transformers feeding 2-wire systems must be grounded at the center of the secondary coils.

2 Transformers feeding systems with a neutral wire must have the neutral wire grounded at the transformer and at least every 250 feet beyond.

Inspection Department having jurisdiction may *require* grounding if they deem it necessary.

Ground Connections.

c. The ground wire in D. C. 3-wire systems must not at Central Stations be smaller than the neutral wire and not smaller than No. 6 B. & S. elsewhere.

d. The ground wire in A. C. systems must never be less than No. 6 B. & S., and must always have equal carrying capacity to the secondary lead of the transformer, or the combined leads where transformers are banked.

e. The ground wire must be kept outside of buildings, but may be directly attached to the building or pole. The wire must be carried in as nearly a straight line as possible, and kinks, coils and sharp bends must be avoided.

f. The ground connection for Central Stations, transformer sub-stations, and banks of transformers must be made through metal plates buried in coke below permanent moisture level, and connection should also be made to all available underground piping systems. For individual transformers and building services the ground connection may be made as above, or may be made to water or other piping systems running into the buildings. This connection may be made by carrying the ground wire into the cellar and connecting on the street side of meters, main clocks, etc.

In connecting ground wires to piping systems, where possible the wires should be soldered into one or more brass plugs and the plugs forcibly screwed into a pipe-fitting, or where the pipes are cast iron into a hole tapped to the pipe itself. For large stations, where connecting to underground pipes with bell and spigot joints, it is well to connect to several lengths, as the pipe joints may be of rather high resistance. Where such plugs cannot be used the surface of the pipe may be filed or scraped bright, the wire wound around it, and a strong clamp put over the wire and firmly bolted together.

Where ground plates are used a No. 16 copper plate, about 3 x 6 feet in size, with about two feet of crushed coke or charcoal about pea size both under and over it, would make a ground of sufficient capacity for a moderate size station, and would probably answer for the ordinary sub-station or bank of transformers. For a large Central Station considerable more area might be necessary, depending upon the other underground connections available. The ground wire should be riveted to such a plate in a number of places, and soldered for its whole length. Perhaps even better than a copperplate is a cast-iron plate with projecting forks, the idea of the fork being to distribute the connection to the ground over a fairly broad area, and to give a large surface contact. The ground wire can probably best be connected to such a cast-iron plate by brass plugs screwed into the plate to which the wire is soldered. In all cases the joint between the plate and the ground wire should be thoroughly protected against corrosion by suitable painting with waterproof paint or some equivalent.

CLASS C.

INSIDE WORK

ALL SYSTEMS AND VOLTAGES.

GENERAL RULES — ALL SYSTEMS AND VOLTAGES.

14. Wires —

(*For special rules See Nos. 18, 24, 32, 38, and 39.*)

a. Must not be of smaller size than No. 14 B. & S., except as allowed under Rules 24 *t* and 45 *b*.

b. Tie wires must have an insulation equal to that of the conductors they confine.

c. Must be so spliced or joined as to be both mechanically and electrically secure without solder; they must be then soldered to insure preservation, and the joint covered with an insulation equal to that on the conductors.

Stranded wires must be soldered before being fastened under clamps or binding screws; and, when they have a conductivity greater than No. 10 B. & S. copper wire, they will be soldered into lugs.

All joints must be soldered, even if made with some form of patent splicing device. This ruling applies to joints and splices in all classes of wiring covered by these rules.

d. Must be separated from contact with walls, floors, timbers, or partitions through which they may pass by non-combustible, non-absorptive insulating tubes, such as glass or porcelain.

Bushings must be long enough to bush the entire length of the hole in one continuous piece, or else the hole must first be bushed by a continuous waterproof tube, which may be a conductor, such as iron pipe; the tube then is to have a non-conducting bushing pushed in at each end so as to keep the wire absolutely out of contact with the conducting pipe.

e. Must be kept free from contact with gas, water, or other metallic piping, or any other conductors or conducting material which they may cross, by some continuous and firmly fixed non-conductor, creating a separation of at least one inch. Deviations from this rule may sometimes be allowed by special permission.

f. Must be so placed in wet places that an air space will be left between conductors and pipes in crossing, and the former must be run in such a way that they cannot come in contact with the pipe accidentally. Wires should be run over, rather than under, pipes upon which moisture is likely to gather or which, by leaking, might cause trouble on a circuit.

15. **Underground Conductors —**

a. Must be protected, when brought into a building, against moisture and mechanical injury, and all combustible material must be kept removed from the immediate vicinity.

b. Must not be so arranged as to shunt the current through a building around any catch-box.

16. **Table Carrying Capacity of Wires —**

Below is a table which must be followed in placing interior conductors, showing the allowable carrying capacity of wires and cables of ninety-eight per cent conductivity, according to the standard adopted by the American Institute of Electrical Engineers.

B. & S. G.	Table A. Rubber-Covered Wires. See No. 41. Amperes.	Table B. Weather-proof Wires. See No. 42 to 44. Amperes.	Circular Mils.	Circular Mils.	Table A. Rubber-Covered Wires. See No. 41. Amperes.	Table B. Weather-proof Wires. See No. 42 to 44. Amperes.
18	3	5	1,624	200,000	200	300
16	6	8	2,583	300,000	270	400
14	12	16	4,107	400,000	330	500
12	17	23	6,530	500,000	390	590
10	24	32	10,380	600,000	450	680
8	33	46	16,510	700,000	500	760
6	46	65	26,250	800,000	550	840
5	54	77	33,100	900,000	600	920
4	65	92	41,740	1,000,000	650	1,000
3	76	110	52,630	1,100,000	690	1,080
2	90	131	66,370	1,200,000	730	1,150
1	107	156	83,690	1,300,000	770	1,220
0	127	185	105,500	1,400,000	810	1,290
00	150	220	133,100	1,500,000	850	1,360
000	177	262	167,800	1,600,000	890	1,430
0000	210	312	211,600	1,700,000	930	1,490
				1,800,000	970	1,550
				1,900,000	1,010	1,610
				2,000,000	1,050	1,670

The lower limit is specified for rubber-covered wires to prevent gradual deterioration of the high insulations by the heat of the wires, but not from fear of igniting the insulation. The question of drop is not taken into consideration in the above tables.

The carrying capacity of sixteen and eighteen wire is given, but no smaller than fourteen is to be used, except as allowed under Rules 24 *t* and 45 *b*.

17. **Switches, Cutouts, Circuit-Breakers, etc.**

(*For construction rules, see Nos.* 51, 52, *and* 53.)

a. Must, whenever called for, unless otherwise provided (for exceptions, see No. 8 *c* and No. 22 *c*), be so arranged that the cutouts will protect, and the opening of the switch or circuit-breaker will disconnect, all of the wires; that is, in a two-wire system the two wires, and in a three-wire system the three wires, must be protected by the cutout, and disconnected by the operation of the switch or circuit-breaker.

b. Must not be placed in the immediate vicinity of easily ignitible stuff or where exposed to inflammable gases or dust or to flyings of combustible material.

c. Must, when exposed to dampness, either be inclosed in a waterproof box or mounted on porcelain knobs.

CONSTANT CURRENT SYSTEMS.

Principally Series Arc Lighting.

18. **Wires** —

(*See also Nos.* 14, 15, *and* 16.)

a. Must have an *approved* rubber insulating covering (see No. 41).

b. Must be arranged to enter and leave the building through an *approved* double-contact service switch (see No. 51), mounted in a non-combustible case, kept free from moisture, and easy of access to police or firemen. So-called "snap switches" must not be used on high-potential circuits.

c. Must always be in plain sight, and never incased, except when *required* by the Inspection Department having jurisdiction.

d. Must be supported on glass or porcelain insulators, which separate the wire at least one inch from the surface wired over, and must be kept *rigidly* at least eight inches from each other, except within the structure of lamps, on hanger-boards, in cutout boxes, or like places, where a less distance is necessary.

e. Must, on side walls, be protected from mechanical injury by a substantial boxing, retaining an air space of one inch around the conductors, closed at the top (the wires passing through bushed holes), and extending not less than seven feet from the floor. When crossing floor-timbers in cellars or in rooms, where they might be exposed to injury, wires must be attached by their insulating supports to the under side of a wooden strip not less than one-half an inch in thickness.

19. **Arc Lamps** —

(*For construction rules, see No.* 57.)

a. Must be carefully isolated from inflammable material.

b. Must be provided at all times with a glass globe surrounding the arc, securely fastened upon a closed base. No broken or cracked globes to be used.

c. Must be provided with a wire netting (having a mesh not exceeding one and one-fourth inches) around the globe, and an *approved* spark arrester (see No. 58), when readily inflammable material is in the vicinity of the lamps, to

prevent escape of sparks, melted copper, or carbon. It is recommended that plain carbons, not copper-plated, be used for lamps in such places.

Arc lamps, when used in places where they are exposed to flyings of easily inflammable material, should have the carbons inclosed completely in a globe in such manner as to avoid the necessity for spark arresters.

For the present, globes and spark arresters will not be required on so-called "inverted arc" lamps, but this type of lamp must not be used where exposed to flyings of easily inflammable materials.

d. Where hanger-boards (see No. 56) are not used, lamps must be hung from insulating supports other than their conductors.

20. **Incandescent Lamps in Series Circuits** —

a. Must have the conductors installed as provided in No. 18, and each lamp must be provided with an automatic cutout.

b. Must have each lamp suspended from a hanger-board by means of rigid tube.

c. No electro-magnetic device for switches and no system of multiple-series or series-multiple lighting will be approved.

d. Under no circumstances can they be attached to gas fixtures.

CONSTANT POTENTIAL SYSTEMS.

GENERAL RULES, ALL VOLTAGES.

21. **Automatic Cutouts** (Fuses and Circuit-Breakers).

(*See No. 17, and for construction Nos. 52 and 53.*)

a. Must be placed on all service wires, either overhead or underground, as near as possible to the point where they enter the building and inside the walls, and arranged to cut off the entire current from the building.

Where the switch required by rule No. 22 is inside the building, the cutout required by this section must be placed so as to protect it.

b. Must be placed at every point where a change is made in the size of wire [unless the cutout in the larger wire will protect the smaller (see No. 16)].

c. Must be in plain sight, or inclosed in an *approved* box (see No. 54) and readily accessible. They must not be placed in the canopies or shells of fixtures.

d. Must be so placed that no set of incandescent lamps, whether grouped on one fixture or several fixtures or pendants, requiring more than 660 watts, shall be dependent upon one cutout. Special permission may be given in writing by the Inspection Department having jurisdiction for departure from this rule in case of large chandeliers, stage borders, and illuminated signs.

e. Must be provided with fuses, the rated capacity of which does not exceed the allowable carrying capacity of the wire; and, when circuit-breakers are used, they must not be set more than about thirty per cent above the allowable carrying capacity of the wire, unless a fusible cutout is also installed in the circuit (see No. 16).

22. **Switches** —

(*See No. 17, and for construction, No. 51.*)

a. Must be placed on all service wires, either overhead or underground in a readily accessible place, as near as possible to the point where the wires enter the building, and arranged to cut off the entire current.

b. Must always be placed in dry, accessible places, and be grouped as far as possible. Knife switches must be so placed that gravity will tend to open rather than close the switch.

c. Must not be single-pole, except when the circuits which they control supply not more than six 16-candle power lamps or their equivalent.

d. Where flush switches are used, whether with conduit systems or not, the switches must be inclosed in boxes constructed of or lined with fire-resisting material. No push-buttons for bells, gas-lighting circuits or the like shall be placed in the same wall-plate with switches controlling electric light or power wiring.

23. **Electric Heaters** —

a. Must, if stationary, be placed in a safe situation, isolated from inflammable materials, and be treated as sources of heat.

b. Must each have a cutout and *indicating*-switch (see No. 17*a*).

c. Must have the attachments of feed wires to the heaters in plain sight, easily accessible, and protected from interference, accidental or otherwise.

d. The flexible conductors for portable apparatus, such as irons, etc., must have an *approved* insulating covering (see No. 45 *h*).

e. Must each be provided with name-plate, giving the maker's name and the normal capacity in volts and amperes.

LOW-POTENTIAL SYSTEMS.

550 Volts or less.

Any circuit attached to any machine, or combination of machines, which develops a difference of potential, between any two wires, of over ten volts and less than 550 volts, shall be considered as a low-potential circuit, and as coming under this class, unless an approved transforming device is used, which cuts the difference of potential down to ten volts or less. The primary circuit not to exceed a potential of 3,500 volts.

24. **Wires** —

GENERAL RULES.

(*See also Nos. 14, 15,* and *16.*)

a. Must not be laid in plaster, cement, or similar finish.

b. Must never be fastened with staples.

c. Must not be fished for any great distance, and only in places where the inspector can satisfy himself that the rules have been complied with.

d. Twin wires must never be used, except in conduits, or where flexible conductors are necessary.

e. Must be protected on side walls from mechanical injury. When crossing floor-timbers in cellars or in rooms, where they might be exposed to injury, wires must be attached by their insulating supports to the under side of a wooden strip, not less than one-half inch in thickness, and not less than three inches in width.

Suitable protection on side walls may be secured by a substantial boxing, retaining an air space of one inch around the conductor, closed at the top (the wires passing through bushed holes), and extending not less than five feet from the floor; or by an iron-armored or metal-sheathed insulating conduit sufficiently strong to withstand the strain it will be subjected to; or plain metal pipe, lined with insulating tubing, which must extend one-half inch beyond the end of the metal tube.

The pipe must extend not less than five feet above the floor, and may extend through the floor in place of a floor bushing.

If iron pipes are used with alternating currents, the two or more wires of a circuit *must* be placed

in the same conduit. In this case the insulation of each wire must be reinforced by a tough conduit tubing projecting beyond the ends of the iron pipe at least two inches.

f. When run immediately under roofs, or in proximity to water tanks or pipes, will be considered as exposed to moisture.

SPECIAL RULES.

For open work:

In dry places:

g. Must have an *approved* rubber or "slow-burning" waterproof insulation (see Nos. 41 and 42).

h. Must be rigidly supported on non-combustible, non-absorptive insulators, which separate the wires from each other and from the surface wired over in accordance with following table:

OLTAGE.	DISTANCE FROM SURFACE.	DISTANCE BETWEEN WIRES.
0 to 225	½ inch.	2½ inches.
225 " 550	1 "	4 "

Rigid supporting requires under ordinary conditions, where wiring along flat surfaces, supports at least every four and one-half feet. If the wires are liable to be disturbed, the distance between supports should be shortened. In buildings of mill construction, mains of No. 8 B. & S. wire or over, where not liable to be disturbed, may be separated about four inches, and run from timber to timber, not breaking around, and may be supported at each timber only.

This rule will not be interpreted to forbid the placing of the neutral of a three-wire system in the center of a three-wire cleat, provided the outside wires are separated in accordance with above table.

In damp places, such as Breweries, Sugar Houses, Packing Houses, Stables, Dye Houses, Paper or Pulp Mills, or buildings specially liable to moisture or acid or other fumes liable to injure the wires or their insulation, except where used for pendants:

i. Must have an *approved* rubber insulating covering (see No. 41).

j. Must be rigidly supported on non-combustible, non-absorptive insulators, which separate the wire at least one inch from the surface wired over, and they must be kept apart at least two and one-half inches.

Rigid supporting requires under ordinary conditions, where wiring over flat surfaces, supports at least every four and one-half feet. If the wires are liable to be disturbed, the distance between supports should be shortened. In buildings of mill construction, mains of No. 8 B. & S. wire or over, where not liable to be disturbed, may be separated about four inches, and run from timber to timber, not breaking around, and may be supported at each timber only.

k. Must have no joints or splices.

For molding work:

l. Must have *approved* rubber insulating covering (see No. 41).

m. Must never be placed in molding in concealed or damp places.

For conduit work:

n. Must have an *approved* rubber insulating covering (see No. 47).

o. Must not be drawn in until all mechanical work on the building has been, as far as possible, completed.

p. Must, for alternating systems, have the two or more wires of a circuit drawn in the same conduit.

It is advised that this be done for direct-current systems also, so that they may be changed to alternating systems at any time, induction troubles preventing such a change unless this construction is followed.

For concealed "knob and tube" work:

q. Must have an *approved* rubber insulating covering (see No. 41).

r. Must be rigidly supported on non-combustible, non-absorptive insulators which separate the wire at least one inch from the surface wired over, and must be kept at least ten inches apart, and, when possible, should be run singly on separate timbers or studding.

Rigid supporting requires under ordinary conditions, where wiring along flat surfaces, supports at least every four and one-half feet. If the wires are liable to be disturbed, the distance between supports should be shortened.

s. When, from the nature of the case, it is impossible to place concealed wiring on non-combustible, insulating supports of glass or porcelain, an *approved* armored cable with single or twin conductors (see No. 48) may be used where the difference of potential between wires is not over 300 volts, provided it is installed without joints between outlets, and the cable armor properly enters all fittings and is rigidly secured in place; or, if the difference of potential between wires is not over 300 volts, and if wires are not exposed to moisture, they may be fished on the loop system if separately incased throughout in approved flexible tubing or conduits.

For fixture work:

t. Must have an *approved* rubber insulating covering (see No. 46), and shall not be less in size than No. 18 B. & S.

u. Supply conductors, and especially the splices to fixture wires, must be kept clear of the grounded part of gas-pipes; and. where shells are used, the latter must be constructed in a manner affording sufficient area to allow this requirement.

v. Must, when fixtures are wired outside, be so secured as not to be cut or abraded by the pressure of the fastenings or motion of the fixture.

25. **Interior Conduits** —

(*See also Nos.* 24 *n to p, and* 49.)

The object of a tube or conduit is to facilitate the insertion or extraction of the conductors to protect them from mechanical injury and, as far as possible, from moisture. Tubes or conduits are to be considered merely as raceways, and are not to be relied upon for insulation between wire and wire, or between the wire and the ground.

a. No conduit tube having an internal diameter of less than five-eighths of an inch shall be used. (If conduit is lined, measurement to be taken inside of lining.)

b. Must be continuous from one junction box to another or to fixtures, and the conduit tube must properly enter all fittings.

c. Must be first installed as a complete conduit system, without the conductors.

d. Must be equipped at every outlet with an *approved* outlet box.

e. Metal conduits, where they enter junction boxes, and at all other outlets, etc., must be fitted with a capping of *approved* insulating material, fitted so as to protect wire from abrasion.

f. Must have the metal of the conduit permanently and effectively grounded.

26. **Fixtures** —

(*See also No.* 24 *t to v.*)

a. Must, when supported from the gas-piping of a building, be insulated from the gas-pipe system by means of *approved* insulating joints (see No. 59) placed as close as possible to the ceiling.

It is recommended that the gas outlet pipe be protected above the insulating joint by a non-combustible, non-absorptive insulating tube, having a flange at the lower end where it comes in contact with

the insulating joint; and that, where outlet tubes are used, they be of sufficient length to extend below the insulating joint, and that they be so secured that they will not be pushed back when the canopy is put in place. Where iron ceilings are used, care must be taken to see that the canopy is thoroughly and permanently insulated from the ceiling.

b. Must have all burs, or fins, removed before the conductors are drawn into the fixture.

c. The tendency to condensation within the pipes should be guarded against by sealing the upper end of the fixture.

d. No combination fixture in which the conductors are concealed in a space less than one-fourth inch between the inside pipe and the outside casing will be approved.

e. Must be tested for "contacts" between conductors and fixture, for "short circuits," and for ground connections before it is connected to its supply conductors.

f. Ceiling blocks for fixtures should be made of insulating material; if not the wires in passing through the plate must be surrounded with non-combustible non-absorptive, insulating material, such as glass or porcelain.

g. Under no conditions shall there be a difference of potential of more than 300 volts between wires contained in or attached to the same fixture

27. **Sockets —**

(*For construction rules, see No. 55.*)

a. In rooms where inflammable gases may exist the incandescent lamp and socket must be inclosed in a vapor-tight globe, and supported on a pipe hanger, wired with *approved* rubber-covered wire (see No. 41) soldered directly to the circuit.

b. In damp or wet places, or over specially inflammable stuff, waterproof sockets must be used.

When waterproof sockets are used, they should be hung by separate stranded rubber-covered wires, not smaller than No. 14 B. & S., which should preferably be twisted together when the drop is over three feet. These wires should be soldered direct to the circuit wires, but supported independently of them.

28. **Flexible Cord —**

a. Must have an *approved* insulation and covering (see No. 45).

b. Must not be used where the difference of potential between the two wires is over 300 volts.

c. Must not be used as a support for clusters.

d. Must not be used except for pendants, wiring of fixtures, and portable lamps or motors.

e. Must not be used in show windows.

f. Must be protected by insulating bushings where the cord enters the socket.

g. Must be so suspended that the entire weight of the socket and lamp will be borne by knots under the bushing in the socket, and above the point where the cord comes through the ceiling block or rosette, in order that the strain may be taken from the joints and binding screws.

29. **Arc Lights on Low-Potential Circuits —**

a. Must have a cutout (see No. 17*a*) for each lamp or each series of lamps.

The branch conductors should have a carrying capacity about fifty per cent in excess of the normal current required by the lamp to provide for heavy current required when lamp is started or when carbons become stuck without overfusing the wires.

b. Must only be furnished with such resistances or regulators as are inclosed in non-combustible material, such resistances being treated as sources of heat. Incandescent lamps must not be used for resistance devices.

c. Must be supplied with globes and protected by spark arresters and wire netting around globe, as in the case of arc lights on high-potential circuits (see Nos. 19 and 58).

30. **Economy Coils —**

a. Economy and compensator coils for arc lamps must be mounted on non-combustible, non-absorptive insulating supports, such as glass or porcelain, allowing an air space of at least one inch between frame and support, and in general to be treated like sources of heat.

31. **Decorative Series Lamps —**

a. Incandescent lamps run in series shall not be used for decorative purposes inside of buildings, except by special permission in writing from the Inspection Department having jurisdiction.

32. **Car Wiring —**

a. Must be always run out of reach of the passengers, and must have an *approved* rubber-insulating covering (see No. 41)

33. **Car Houses —**

a. Must have the trolley wires securely supported on insulating hangers.

b. Must have the trolley hangers placed at such distance apart that, in case of a break in the trolley wire, contact cannot be made with the floor.

c. Must have cutout switch located at a proper place outside of the building, so that all trolley circuits in the building can be cut out at one point, and line circuit-breakers must be installed, so that when this cutout switch is open the trolley wire will be dead at all points within 100 feet of the building. The current must be cut out of the building whenever the same is not in use or the road not in operation.

d. Must have all lamps and stationary motors installed in such a way that one main switch can control the whole of each installation — lighting or power — independently of main feeder-switch. No portable incandescent lamps or twin wire allowed, except that portable incandescent lamps may be used in the pits, connections to be made by two *approved* rubber-covered flexible wires (see No. 41), properly protected against mechanical injury; the circuit to be controlled by a switch placed outside of the pit.

e. Must have all wiring and apparatus installed in accordance with rules under Class "C" for constant potential systems.

f. Must not have any system of feeder distribution centering in the building.

g. Must have the rails bonded at each joint with no less than No. 2 B. & S. annealed copper wire, also a supplementary wire to be run for each track.

h. Must not have cars left with trolley in electrical connection with the trolley wire.

34. Lighting and Power from Railway Wires —

a. Must not be permitted, under any pretense, in the same circuit with trolley wires with a ground return, except in electric railway cars, electric car houses and their power stations; nor shall the same dynamo be used for both purposes.

HIGH-POTENTIAL SYSTEMS.

550 TO 3,500 VOLTS.

Any circuit attached to any machine, or combination of machines, which develops a difference of potential, between any two wires, of over 300 volts and less than 3,500 volts, shall be considered as a high-potential circuit, and as coming under that class, unless an approved transforming device is used, which cuts the difference of potential down to 300 volts or less.

35. **Wires** —

(*See also Nos. 14, 15, and 16.*)

a. Must have an *approved* rubber-insulating covering (see No. 41).

b. Must be always in plain sight and never incased, except where required by the Inspection Department having jurisdiction.

c. Must be rigidly supported on glass or porcelain insulators, which raise the wire at least one inch from the surface wired over, and must be kept apart at least four inches for voltages up to 750 and at least eight inches for voltages over 750.

Rigid supporting requires under ordinary conditions, where wiring along flat surfaces, supports at least about every four and one-half feet. If the wires are unusually liable to be disturbed, the distance between supports should be shortened.

In buildings of mill construction, mains of No. 8 B. & S. wire or over, where not liable to be disturbed, may be separated about six inches for voltages up to 750 and about ten inches for voltages above 750; and run from timber to timber, not breaking around, and may be supported at each timber only.

d. Must be protected on side walls from mechanical injury by a substantial boxing, retaining an air space of one inch around the conductors, closed at the top (the wires passing through bushed holes) and extending not less than seven feet from the floor. When crossing floor-timbers, in cellars or in rooms, where they might be exposed to injury, wires must be attached by their insulating supports to the under side of a wooden strip not less than one-half an inch in thickness.

36. **Transformers** (when permitted inside buildings, see No. 13) —

(*For construction rules, see No. 62.*)

a. Must be located at a point as near as possible to that at which the primary wires enter the building.

b. Must be placed in an inclosure constructed of or lined with fire-resisting material: the inclosure to be used only for this purpose, and to be kept securely locked, and access to the same allowed only to responsible persons.

c. Must be effectually insulated from the ground, and the inclosure in which they are placed must be practically air-tight, except that it shall be thoroughly ventilated to the outdoor air, if possible, through a chimney or flue. There should be at least six inches air space on all sides of the transformer.

37. **Series Lamps** —

a. No system of multiple-series or series-multiple for light or power will be approved.

b. Under no circumstances can lamps be attached to gas fixtures.

EXTRA HIGH-POTENTIAL SYSTEMS.

OVER 3,500 VOLTS.

Any circuit attached to any machine or combination of machines, which develops a difference of potential, between any two wires, of over 3,500 volts, shall be considered as an extra high-potential circuit, and as coming under that class, unless an approved transforming device is used, which cuts the difference of potential down to 3,500 volts or less.

38. **Primary Wires —**

a. Must not be brought into or over building, except power and substations.

39. **Secondary Wires —**

a. Must be installed under rules for high-potential systems, when their immediate primary wires carry a current of over 3,500 volts, unless the primary wires are entirely underground, within city and village limits.

The presence of wires carrying a current with a potential of over 3,500 volts in the streets of cities, towns, and villages is considered to increase the fire hazard. Extra high potential circuits are also objectionable in any location where telephone, telegraph, and similar circuits run in proximity to them. As the underwriters have no jurisdiction over streets and roads they can only take this indirect way of discouraging such systems; but further, it is strongly urged that municipal authorities absolutely refuse to grant any franchise for right of way for overhead wires carrying a current of extra high potential through streets or roads which are used to any great extent for public travel or for trunk-line, telephone, or telegraph circuits.

CLASS D.

FITTINGS, MATERIALS, AND DETAILS OF CONSTRUCTION.

All Systems and Voltages.

Insulated Wires — Rules 40 to 48.

40. **General Rules —**

a. Copper for insulated conductors must never vary in diameter so as to be more than two one-thousandths of an inch less than the specified size.

b. Wires and cables of all kinds designed to meet the following specifications must be plainly tagged or marked as follows:

1. The maximum voltage at which the wire is designed to be used.
2. The words "National Electrical Code Standard."
3. Name of the manufacturing company, and, if desired, trade-name of the wire.
4. Month and year when manufactured.

41. **Rubber-Covered —**

a. Copper for conductors must be thoroughly tinned.

Insulation for voltages between 0 and 600:

b. Must be of rubber or other approved substance, and be of a thickness not less than that given in the following table for B. & S. gauge sizes:

From	18 to	16,	inclusive,		$\frac{1}{32}''$
"	14 to	8,	"		$\frac{3}{64}''$
"	7 to	2,	"		$\frac{1}{16}''$
"	1 to	0000,	"		$\frac{5}{64}''$
"	0000 to	500,000,	C. M.		$\frac{3}{32}''$
"	500,000 to	1,000,000,	"		$\frac{7}{64}''$
Larger than		1,000,000,	"		$\frac{1}{8}''$

Measurements of insulating wall are to be made at the thinnest portion of the dielectric.

c. The completed coverings must show an insulation resistance of at least 100 megohms per mile during thirty days' immersion in water at seventy degrees Fahrenheit.

d. Each foot of the completed covering must show a dielectric strength sufficient to resist throughout five minutes the application of an electro-motive force of 3,000 volts per one-sixty-fourth of an inch thickness of insulation under the following conditions:

The source of alternating electro-motive force shall be a transformer of at least one kilowatt capacity. The application of the electro-motive force shall first be made at 4,000 volts for five minutes and then the voltage increased by steps of not over 3,000 volts, each held for five minutes, until the rupture of the insulation occurs. The tests for dielectric strength shall be made on a sample of wire which has been immersed for seventy-two hours in water, one foot of which is submerged in a conducting liquid held in a metal trough, one of the transformer terminals being connected to the copper of the wire and the other to the metal of the trough.

Insulations for voltages between 600 and 3,500:

e. The thickness of the insulating walls must not be less than those given in the following table for B. & S. gauge sizes:
From 14 to 1, inclusive, $\frac{3}{32}''$
From 0 to 500,000, C. M., $\frac{3}{32}''$ covered by a tape or a braid.
Larger than 500,000, C. M., $\frac{4}{32}''$ covered by a tape or a braid.

f. The requirements as to insulation and break-down resistance for wires for low-potential systems shall apply, with the exception that an insulation resistance of not less than 300 megohms per mile shall be required.

g. Wire for arc-light circuits exceeding 3,500 volts potential shall have an insulating wall not less than six-thirty-seconds of an inch in thickness, and shall withstand a break-down test of at least 30,000 volts and have an insulation of at least 500 megohms per mile.

The tests on this wire to be made under the same conditions as for low-potential wires.

Specifications for insulations for alternating currents exceeding 3,500 volts have been considered, but on account of the somewhat complex conditions in such work, it has so far been deemed inexpedient to specify general insulations for this use.

h. All of the above insulations must be protected by a substantial braided covering properly saturated with a preservative compound and sufficiently strong to withstand all the abrasion likely to be met with in practice, and sufficiently elastic to permit all wires smaller than No. 7 B. & S. gage to be bent around a cylinder with twice the diameter of the wire, without injury to the braid.

42. **Slow-burning Weatherproof** —

a. The insulation shall consist of two coatings, the inner one to be fireproof in character, the outer to be weatherproof. The inner fireproof coating must comprise at least six-tenths of the total thickness of the wall. The completed covering must be of a thickness not less than that given in the following table for B. & S. gauge sizes:

From	14 to	8,	inclusive,		3/64″
"	7 to	2,			1/16″
"	2 to	0000,			5/64″
"	0000 to	500,000,	C. M.,		3/32″
"	500,000 to	1,000,000,	"		7/64″
Larger than		1,000,000,	"		1/8″

Measurements of insulating wall are to be made at the thinnest portion of the dielectric.

b. The inner fireproof coating shall be layers of cotton or other thread, the outer one of which must be braided. All the interstices of these layers are to be filled with the fireproofing compound. This is to be material whose solid constituent is not susceptible to moisture, and which will not burn even when ground in an oxidizable oil, making a compound which, while proof against fire and moisture, at the same time has considerable elasticity, and which when dry will suffer no change at a temperature of 250 degrees Fahrenheit, and which will not burn at even higher temperature.

c. The weatherproof coating shall be a stout braid thoroughly saturated with a dense moistureproof compound thoroughly slicked down, applied in such manner as to drive any atmospheric moisture from the cotton braiding, thereby securing a covering to a great degree waterproof and of high insulating power. This compound to retain its elasticity at zero Fahrenheit, and not to drip at 160 degrees Fahrenheit.

This wire is not as burnable as the old "weatherproof," nor as subject to softening under heat, but still is able to repel the ordinary amount of moisture found indoors. It would not usually be used for outside work.

43. **Slow-burning** —

a. The insulation shall be the same as the "slow-burning weatherproof," except that the outer braiding shall be impregnated with a fireproofing compound similar to that required for the interior layers, and with the outer surface finished smooth and hard.

This "slow-burning" wire shall only be used with special permission of the Inspection Department having jurisdiction.

This is practically the old "Underwriters'" insulation. It is specially useful in hot, dry places where ordinary insulations would perish, also where wires are bunched, as on the back of a large

switchboard or in a wire tower, so that the accumulation of rubber or weatherproof insulation would result in an objectionably large mass of highly inflammable material.

Its use is restricted, as its insulating qualities are not high and are damaged by moisture.

44. Weatherproof —

a. The insulating covering shall consist of at least three braids thoroughly impregnated with a dense moisture repellent, which will not drip at a temperature lower than 180 degrees Fahrenheit. The thickness of insulation shall be not less than that of "slow-burning weatherproof." The outer surface shall be thoroughly slicked down."

This wire is for outdoor use where moisture is certain and where fireproof qualities are not necessary.

45. Flexible Cord —

a. Must be made of stranded copper conductors, each strand to be not larger than No. 26 or smaller than No. 30 B. & S. gauge, and each stranded conductor must be covered by an approved insulation and protected from mechanical injury by a tough braided outer covering.

For pendent lamps:

In this class is to be included all flexible cord which under usual conditions hangs freely in air, and which is not likely to be moved sufficiently to come in contact with surrounding objects.

b. Each stranded conductor must have a carrying capacity equivalent to not less than a No. 18 B. & S. gauge wire.

c. The covering of each stranded conductor must be made up as follows:

1. A tight, close wind of fine cotton.
2. The insulation proper, which shall be either waterproof or slow-burning.
3. An outer cover of silk or cotton.

The wind of cotton tends to prevent a broken strand puncturing the insulation and causing a short circuit. It also keeps the rubber from corroding the copper.

d. Waterproof insulation must be solid, at least one-thirty-second of an inch thick, and must show an insulation resistance of fifty megohms per mile throughout two weeks' immersion in water at 70 degrees Fahrenheit, and stand the tests prescribed for low-tension wires as far as they apply.

e. Slow-burning insulation must be at least one-thirty-second of an inch in thickness, and composed of substantial, elastic, slow-burning materials, which will suffer no damage at a temperature of 250 degrees Fahrenheit.

f. The outer protecting braiding should be so put on and sealed in place that when cut it will not fray out, and where cotton is used, it should be impregnated with a flameproof paint, which will not have an injurious effect on the insulation.

For portables:

In this class is included all cord used on portable lamps, small portable motors, etc.

g. Flexible cord for portable use must have waterproof insulation as required in section *d* for pendent cord, and in addition be provided with a reinforcing cover especially designed to withstand the abrasion it will be subject to in the uses to which it is to be put.

For portable heating apparatus:

h. Must be made up as follows: —

1. A tight, close wind of fine cotton.
2. A thin layer of rubber about one-one-hundredth of an inch thick, or other cementing material.
3. A layer of asbestos insulation at least three-sixty-fourths of an inch thick.
4. A stout braid of cotton.
5. An outer reinforcing cover especially designed to withstand abrasion.

This cord is in no sense waterproof, the thin layer of rubber being specified in order that it may serve merely as a seal to help hold in place the fine cotton and asbestos, and it should be so put on as to accomplish this.

46. **Fixture Wire** —

a. Must have a solid insulation, with a slow-burning, tough, outer covering, the whole to be at one-thirty-second of an inch in thickness, and show an insulation resistance between conductors, and between either conductor and the ground, of at least one megohm per mile, after one week's submersion in water at seventy degrees Fahrenheit, and after three minutes' electrification, with 550 volts.

47. **Conduit Wire** —

Must comply with the following specifications:

a. For metal conduits, having a lining of insulating material, single wires must comply with No. 41, and all duplex, twin, and concentric conductors must comply with No. 41, and must also have each conductor separately braided or taped and a substantial braid covering the whole.

b. For unlined metal conduits, conductors must conform to the specifications given for lined conduits, and in addition have a second outer fibrous covering at least one-thirty-second of an inch in thickness, and sufficiently tenacious to withstand the abrasion of being hauled through the metal conduit.

The braid required around each conductor in duplex, twin, and concentric cables is to hold the rubber insulation in place and prevent jamming and flattening.

48. **Armored Cable** —

a. The armor of such cables must be at least equal in thickness and of equal strength to resist penetration by nails, etc., as the armor of metal coverings of metal conduits (see No. 49 *b*).

b. The conductors in same, single wire or twin conductors, must have an insulating covering as required by No. 41, any filler used to secure a round exterior must be impregnated with a moisture repellent, and the whole bunch of conductors and fillers must have a separate exterior covering of insulating material at least one-thirty-second of an inch in thickness, conforming to the insulation standard given in No. 41, and covered with a substantial braid.

Very reliable insulation is specified, as such cables are liable to hard usage, and in part of their length may be subject to moisture, while they may not be easily removable, so that a breakdown of insulation is likely to be expensive.

49. Interior Conduits —

(*For wiring rules, see Nos. 24 and 25.*)

a. Each length of conduit, whether insulated or uninsulated, must have the maker's name or initials stamped in the metal or attached thereto in a satisfactory manner, so that the inspectors can readily see the same.

METAL CONDUITS WITH LINING OF INSULATING MATERIAL.

b. The metal covering or pipe must be equal in strength to the ordinary commercial forms of gas-pipe of the same size, and its thickness must be not less than that of standard gas-pipe, as shown by the following table:

Size. Inches.	Thickness of Wall — Inches.	Size. Inches.	Thickness of Wall — inches.
½	.100	1¼	.140
⅝	.111	1½	.145
¾	.113	2	.154
1	.134		

An allowance of two-one-hundredths of an inch for variation in manufacturing and loss of thickness by cleaning will be permitted.

c. Must not be seriously affected externally by burning out a wire inside the tube when the iron pipe is connected to one side of the circuit.

d. Must have the insulating lining firmly secured to the pipe.

e. The insulating lining must not crack or break when a length of the conduit is uniformly bent at temperature of 212 degrees Fahrenheit to an angle of ninety degrees, with a curve having a radius of fifteen inches, for pipes of one inch and less, and fifteen times the diameter of pipe for larger pipes.

f. The insulating lining must not soften injuriously at a temperature below 212 degrees Fahrenheit, and must leave water in which it is boiled practically neutral.

g. The insulating lining must be at least one-thirty-second of an inch in thickness, and the materials of which it is composed must be of such a nature as will not have a deteriorating effect on the insulation of the conductor, and be sufficiently tough and tenacious to withstand the abrasion test of drawing long lengths of conductors in and out of same.

h. The insulating lining must not be mechanically weak after three days' submersion in water, and when removed from the pipe entire must not absorb more than ten per cent of its weight of water during 100 hours of submersion.

i. All elbows or bends must be so made that the conduit or lining of same will not be injured. The radius of the curve of the inner edge of any elbow not to be less than three and one-half inches. Must have not more than the equivalent of four quarter bends from outlet to outlet, the bends at the outlets not being counted.

UNLINED METAL CONDUITS.

j. Plain iron or steel pipes of equal thickness and strengths specified for lined conduits in No. 49 *b* may be used as conduits, provided their interior surfaces are smooth and free from burs; pipe to be galvanized, or the interior surfaces coated or enameled, to prevent oxidation, with some substance which will not soften so as to become sticky and prevent wire from being withdrawn from the pipe.

k. All elbows or bends must be so made that the conduit will not be injured. The radius of the curve of the inner edge of any elbow not to be less than three and one-half inches. Must have not more than the equivalent of four quarter bends from outlet to outlet, the bends at the outlet not being counted.

50. **Wooden Moldings** —

(*For wiring rules, see No. 24.*)

a. Must have, both outside and inside, at least two coats of waterproof paint, or be impregnated with a moisture repellent.

b. Must be made of two pieces, a backing and capping so constructed as to thoroughly incase the wire, and provide a one-half-inch tongue between the conductors, and a solid backing, which, under grooves, shall not be less than three-eighths of an inch in thickness, and must afford suitable protection from abrasion.

It is recommended that only hardwood molding be used.

51. **Switches** —

(*See Nos. 17 and 22.*)

a. Must be mounted on non-combustible, non-absorptive, insulating bases, such as slate or porcelain.

b. Must have carrying capacity sufficient to prevent undue heating.

c. Must, when used for service switches, indicate, on inspection, whether the current be "on" or "off."

d. Must be plainly marked, where it will always be visible, with the name of the maker and the current and voltage for which the switch is designed.

e. Must, for constant potential systems, operate successfully at fifty per cent overload in amperes, with twenty-five per cent excess voltage under the most severe conditions they are liable to meet with in practice.

f. Must, for constant potential systems, have a firm and secure contact; must make and break readily, and not stop when motion has once been imparted by the handle.

g. Must, for constant current systems, close the main circuit and disconnect the branch wires when turned "off"; must be so constructed that they shall be automatic in action, not stopping between points when started, and must prevent an arc between the points under all circumstances. They must indicate, upon inspection, whether the current be "on" or "off."

52. **Cutouts and Circuit-Breakers** —

(*For installation rules, see Nos. 17 and 21.*)

a. Must be supported on bases of non-combustible, non-absorptive insulating material.

b. Cutouts must be provided with covers, when not arranged in approved cabinets, so as to obviate any danger of the melted fuse metal coming in contact with any substance which might be ignited thereby.

c. Cutouts must operate successfully, under the most severe conditions they are liable to meet with in practice, on short circuits with fuses rated at fifty per cent above, and with a voltage twenty-five per cent above the current and voltage for which they are designed.

d. Circuit-breakers must operate successfully, under the most severe conditions they are liable to meet with in practice, on short circuits when set at fifty per cent above the current, and with a voltage twenty-five per cent above that for which they are designed.

e. Must be plainly marked, where it will always be visible, with the name of the maker, and current and voltage for which the device is designed.

53. Fuses —

(*For installation rules, see Nos. 17 and 21.*)

a. Must have contact surfaces or tips of harder metal having perfect electrical connection with the fusible part of the strip.

b. Must be stamped with about eighty per cent of the maximum current they can carry indefinitely, thus allowing about twenty-five per cent overload before fuse melts.

With naked open fuses, of ordinary shapes and not over 500 amperes capacity, the *maximum* current which will melt them in about five minutes may be safely taken as the melting point, as the fuse practically reaches its maximum temperature in this time. With larger fuses a longer time is necessary.

Inclosed fuses where the fuse is often in contact with substances having good conductivity to heat and often of considerable volume, require a much longer time to reach a maximum temperature, on account of the surrounding material which heats up slowly.

These data are given to facilitate testing.

c. Fuse terminals must be stamped with the maker's name, initials, or some known trade-mark.

54. Cutout Cabinets —

a. Must be so constructed, and cutouts so arranged, as to obviate any danger of the melted fuse metal coming in contact with any substance which might be ignited thereby.

A suitable box can be made of marble, slate, or wood, strongly put together, the door to close against a rabbet so as to be perfectly dust-tight, and it should be hung on strong hinges, and held closed by a strong hook or catch. If the box is wood, the inside should be lined with sheets of asbestos board about one-sixteenth of an inch in thickness, neatly put on and firmly secured in place by shellac and tacks. The wire should enter through holes bushed with porcelain bushings; the bushings tightly fitting the holes in the box, and the wires tightly fitting the bushings (using tape to build up the wire, if necessary) so as to keep out the dust.

55. Sockets —

(*See No. 27.*)

Sockets of all kinds, including wall receptacles, must be constructed in accordance with the following specifications: —

a. Standard Sizes.— The standard lamp socket shall be suitable for use on any voltage not exceeding 250 and with any size lamp up to fifty candle-power. For lamps larger than fifty candle-power a standard keyless socket may be used, or if a key is required, a special socket designed for the current to be used must be made. Any special sockets must follow the general spirit of these specifications.

b. Marking. — The standard socket must be plainly marked fifty candle-power, 250 volts, and with either the manufacturer's name or registered trade-

mark. Special large sockets must be marked with the current and voltage for which they are designed.

c. SHELL.— Metal used for shells must be moderately hard, but not hard enough to be brittle or so soft as to be easily dented or knocked out of place. Brass shells must be at least 0.013 inch in thickness, and shells of any other material must be thick enough to give the same stiffness and strength of brass.

d. LINING.— The inside of the shells must be lined with insulating material, which shall absolutely prevent the shell from becoming a part of the circuit, even though the wires inside the socket should start from their position under binding screws.

The material used for lining must be at least one-thirty-second of an inch in thickness, and must be tough and tenacious. It must not be injuriously affected by the heat from the largest lamp permitted in the socket, and must leave the water in which it is boiled practically neutral. It must be so firmly secured to the shell that it will not fall out with ordinary handling of the socket. It is preferable to have the lining in one piece.

e. CAP.— Caps when of sheet brass must be at least 0.013 inch in thickness, and when cast or made of other metals must be of equivalent strength. The inlet piece, except for special sockets, must be tapped and threaded for ordinary one-eighth-inch pipe. It must contain sufficient metal for a full, strong thread, and, when not of the same piece as the cap, must be joined to it in a way to give the strength of a single piece.

There must be sufficient room in the cap to enable the ordinary wireman to easily and quickly make a knot in the cord and push it into place in cap without crowding. All parts of the cap upon which the knot is likely to bear must be smooth and well insulated.

f. FRAME AND SCREWS.— The frame holding moving parts must be sufficiently heavy to give ample strength and stiffness.

Brass pieces containing screw threads must be at least 0.06 of an inch in thickness.

Binding post screws must not be smaller than No. 5 wire and about forty threads per inch.

g. SPACING.— Points of opposite polarity must everywhere be kept not less than three-sixty-fourths of an inch apart unless separated by a reliable insulation.

h. CONNECTIONS.— The connecting points for the flexible cord must be made to very securely grip a No. 16 or 18 B. & S. conductor. A turned-up lug, arranged so that the cord may be gripped between the screw and the lug in such a way that it cannot possibly come out, is strongly advised.

i. LAMP HOLDER.— The socket must firmly hold the lamp in place so that it cannot be easily jarred out, and must provide a contact good enough to prevent undue heating with maximum current allowed. The holding pieces, springs and the like, if a part of the circuit, must not be sufficiently exposed to allow them to be brought in contact with anything outside of lamp and socket.

j. BASE.— The inside parts of the socket, which are of insulating material, except the lining, must be made of porcelain.

k. KEY.— The socket key-handle must be of such a material that it will not soften from the heat of a fifty candle-power lamp hanging downwards in

air at seventy degrees Fahrenheit from the socket, and must be securely, but not necessarily rigidly, attached to the metal spindle it is designed to turn.

l. SEALING.— All screws in porcelain pieces, which can be firmly sealed in place, must be so sealed by a waterproof compound which will not melt below 200 degrees Fahrenheit.

m. PUTTING TOGETHER. — The socket must, as a whole, be so put together that it will not rattle to pieces. Bayonet joints or equivalent are recommended.

n. TEST.— The socket when slowly turned "on and off," at the rate of about two or three times per minute, must "make and break" the circuit 6,000 times before failing, when carrying a load of one ampere at 220 volts.

o. KEYLESS SOCKETS. — Keyless sockets of all kinds must comply with requirements for key sockets as far as they apply.

p. SOCKETS OF INSULATING MATERIALS. — Sockets made of porcelain or other insulating material must conform to the above requirements as far as they apply, and all parts must be strong enough to withstand a moderate amount of hard usage without breaking.

q. INLET BUSHING.— When the socket is not attached to fixtures the threaded inlet must be provided with a strong insulating bushing, having a *smooth* hole of at least fifteen-sixty-fourths of an inch in diameter. The corners of the bushing must be rounded and all inside fins removed, so that in no place will the cord be subjected to the cutting or wearing action of a sharp edge.

56. **Hanger-boards —**

a. Hanger-boards must be so constructed that all wires and current-carrying devices thereon shall be exposed to view, and thoroughly insulated by being mounted on a non-combustible, non-absorptive insulating substance. All switches attached to the same must be so constructed that they shall be automatic in their action, cutting off both poles to the lamp, not stopping between points when started, and preventing an arc between points under all circumstances.

57. **Arc Lamps —**

(*For installation rules, see No. 19.*)

a. Must be provided with reliable stops to prevent carbons from falling out in case the clamps become loose.

b. Must be carefully insulated from the circuit in all their exposed parts.

c. Must, for constant-current systems, be provided with an *approved* hand switch, also an automatic switch that will shunt the current around the carbons, should they fail to feed properly.

The hand switch to be approved, if placed anywhere except on the lamp itself, must comply with requirements for switches on hanger-boards as laid down in No. 56.

58. **Spark Arresters —**

(*See No. 19 c.*)

a. Spark arresters must so close the upper orifice of the globe that it will be impossible for any sparks thrown off by the carbons to escape.

59. Insulating Joints —

(*See No. 26 a.*)

a. Must be entirely made of material that will resist the action of illuminating gases, and will not give way or soften under the heat of an ordinary gas flame or leak under a moderate pressure. They shall be so arranged that a deposit of moisture will not destroy the insulating effect, and shall have an insulating resistance of at least 250,000 ohms between the gas-pipe attachments, and be sufficiently strong to resist the strain they will be liable to be subjected to in being installed.

b. Insulating joints having soft rubber in their construction will not be approved.

60. Resistance Boxes and Equalizers —

(*For installation rules, see No. 4.*)

a. Must be equipped with metal, or with other non-combustible frames.

The word "frame" in this section relates to the entire case and surroundings of the rheostat, and not alone to the upholding supports.

61. Reactive Coils and Condensers —

a. Reactive coils must be made of non-combustible material, mounted on non-combustible bases, and treated, in general, like sources of heat.

b. Condensers must be treated like apparatus operating with equivalent voltage and currents. They must have non-combustible cases and supports, and must be isolated from all combustible materials, and, in general, treated like sources of heat.

62. Transformers —

(*For installation rules, see Nos. 11, 13, and 33.*)

a. Must not be placed in any but metallic or other non-combustible cases.

b. Must be constructed to comply with the following tests:

1. Shall be run for eight consecutive hours at full load in watts under conditions of service, and at the end of that time the rise in temperature, as measured by the increase of resistance of the primary coil, shall not exceed 135 degrees Fahrenheit.
2. The insulation of transformers when heated shall withstand continuously for five minutes a difference of potential of 10,000 volts (alternating) between primary and secondary coils and core, and between the primary coils and core and a no-load "run" at double voltage for thirty minutes.

63. Lightning Arresters —

(*For installation rules, See No. 5.*)

a. Must be mounted on non-combustible bases, and must be so constructed as not to maintain an arc after the discharge has passed, and must have no moving parts.

CLASS E.

MISCELLANEOUS.

64. **Signaling Systems** (governing wiring for telephone, telegraph, district messenger, and call-bell circuits, fire and burglar alarms, and all similar systems) —

a. Outside wires should be run in underground ducts or strung on poles and, as far as possible, kept off of buildings, and must not be placed on the same cross-arm with electric light or power wires.

b. When outside wires are run on same pole with electric light or power wires, the distance between the two inside pins of each cross-arm must not be less than twenty-six inches.

c. All aerial conductors and underground conductors which are directly connected to aerial wires must be provided with some approved protective device, which shall be located as near their point of entrance to the building as possible, and not less than six inches from curtains or other inflammable material.

d. If the protector is placed inside of building, wires, from outside support to binding-posts of protector, shall comply with the following requirements:

1. Must be of copper, and not smaller than No. 16 B. & S. gauge.
2. Must have an *approved* rubber insulating covering (see No. 41).
3. Must have drip loops in each wire immediately outside the building.
4. Must enter buildings through separate holes sloping upward from the outside; when practicable, holes to be bushed with non-absorptive, non-combustible insulating tubes extending through their entire length. Where tubing is not practicable, the wires shall be wrapped with two layers of insulating tape.
5. Must be supported on porcelain insulators, so that they will not come in contact with anything other than their designed supports.
6. A separation between wires of at least two and one-half inches must be maintained.

In case of crosses these wires may become a part of a high-voltage circuit, so that similar care to that given high-voltage circuits is needed in placing them. Reliable porcelain bushings at the entrance holes are desirable, and are only waived under adverse conditions, because the state of the art in this type of wiring makes an absolute requirement inadvisable.

e. The ground wire of the protective device shall be run in accordance with the following requirements:

1. Shall be of copper, and not smaller than No. 16 B. & S.
2. Must have an *approved* rubber insulating covering (see No. 41).
3. Shall run in as straight a line as possible to a good permanent ground, to be made by connecting to water- or gas-pipe, preferably water-pipe. If gas-pipe is used, the connection, in all cases, must be made between the meter and service pipes. In the absence of other good ground, the ground shall be made by means of a metallic plate or bunch of wires buried in permanently moist earth.

4. Shall be kept at least three inches from all other conductors and supported on porcelain insulators, so as not to come in contact with anything other than its designed supports.

In attaching a ground wire to a pipe, it is often difficult to make a thoroughly reliable solder joint. It is better, therefore, where possible, to carefully solder the wire to a brass plug, which may then be firmly screwed into a pipe fitting.

Where such joints are made under ground, they should be thoroughly painted and taped to prevent corrosion.

f. The protector to be approved must comply with the following requirements:

1. Must be mounted on non-combustible, non-absorptive insulating bases, so designed that when the protector is in place, all parts which may be alive will be thoroughly insulated from the wall holding the protector.

2. Must have the following parts:
   A lightning arrester which will operate with a difference of potential between wires of not over 500 volts, and so arranged that the chance of accidental grounding is reduced to a minimum.
   A fuse designed to open the circuit in case the wires become crossed with light or power circuits. The fuse must be able to open the circuit without arcing or serious flashing when crossed with any ordinary commercial light or power circuit.
   A heat coil which will operate before a sneak current can damage the instrument the protector is guarding.

   The heat coil is designed to warm up and melt out with a current large enough to endanger the instruments if continued for a long time, but so small that it would not blow the fuses ordinarily found necessary for such instruments. These smaller currents are often called "sneak" currents.

3. The fuses must be so placed as to protect the arrester and heat coils, and the protector terminals must be plainly marked "line," "instrument," "ground."

g. Wires beyond the protector, except where bunched, must be neatly arranged and securely fastened in place in any convenient, workmanlike manner. They must not come nearer than six inches to any electric light or power wire in the building, unless incased in approved tubing so secured as to prevent its slipping out of place.

The wires would ordinarily be insulated, but the kind of insulation is not specified, as the protector is relied upon to stop all dangerous currents. Porcelain tubing or circular loom conduit may be used for incasing wires where required as above.

h. Wires connected with outside circuits, where bunched together within any building, or inside wires, where laid in conduits or ducts, with electric light or power wires, must have fire-resisting coverings, or else must be inclosed in an air-tight tube or duct.

It is feared that if a burnable insulation were used, a chance spark might ignite it and cause a serious fire, for many installations contain a large amount of very readily burnable matter.

65. Electric Gas Lighting —

Where electric gas lighting is to be used on the same fixture with the electric light:

a. No part of the gas-piping or fixture shall be in electric connection with the gas-lighting circuit.

b. The wires used with the fixtures must have a non-inflammable insulation, or, where concealed between the pipe and shell of the fixture, the insulation must be such as required for fixture wiring for the electric light.

c. The whole installation must test free from "grounds."

d. The two installations must test perfectly free from connection with each other.

66. **Insulation Resistance** —

The wiring in any building must test free from grounds; i.e., the complete installation must have an insulation between conductors and between all conductors and the ground (not including attachments, sockets, recepticles, etc.) of not less than the following:

Up to	5 amperes	. . . .	4,000,000 ohms.
"	10 "	. . . .	2,000,000 "
"	25 "	. . . .	800,000 "
"	50 "	. . . .	400,000 "
"	100 "	. . . .	200,000 "
"	200 "	. . . .	100,000 "
"	400 "	. . . .	25,000 "
"	800 "	. . . .	25,000 "
"	1,600 "	. . . .	12,500 "

All cutouts and safety devices in place in the above.

Where lamp sockets, receptacles, and electroliers, etc., are connected, one-half of the above will be required.

67. **Soldering Fluid** —

a. The following formula for soldering fluid is suggested:

Saturated solution of zinc chloride	5 parts
Alcohol	4 parts
Glycerine	1 part

Class F.

MARINE WORK.

68. **Generators** —

a. Must be located in a dry place.

b. Must have their frames insulated from their bed-plates.

c. Must each be provided with a waterproof cover.

d. Must each be provided with a name-plate, giving the maker's name, the capacity in voltage and amperes and normal speed in revolutions per minute.

69. **Wires** —

a. Must have an *approved* insulating covering.

The insulation for all conductors, except for portables, to be approved, must be at least one-eighth-inch in thickness and be covered with a substantial waterproof and flameproof braid. The physical characteristics shall not be affected by any change in temperature up to 200 degrees Fahrenheit. After two weeks' submersion in salt water at seventy degrees Fahrenheit it must show an insulation resistance of one megohm per mile after three minutes' electrification, with 550 volts.

b. Must have no single wire larger than No. 12 B. & S. Wires to be stranded when greater carrying capacity is required. No single solid wire smaller than No. 14 B. & S., except in fixture wiring, to be used.

Stranded wires must be soldered before being fastened under clamps or binding screws, and when they have a conductivity greater than No. 10 B. & S. copper wire they must be soldered into lugs.

c. Must be supported in approved molding, except at switch boards and portables.

Special permission may be given for deviation from this rule in dynamo-rooms.

d. Must be bushed with hard-rubber tubing one-eighth of an inch in thickness when passing through beams and non-water-tight bulkheads.

e. Must have, when passing through water-tight bulkheads and through all decks, a metallic stuffing tube lined with hard rubber. In case of deck tubes they shall be boxed near deck to prevent mechanical injury.

f. Splices or taps in conductors must be avoided as far as possible. Where it is necessary to make them they must be so spliced or joined as to be both mechanically and electrically secure without solder. They must then be soldered, to insure preservation, covered with an insulating compound equal to the insulation of the wire, and further protected by a waterproof tape. The joint must then be coated or painted with a waterproof compound.

70. **Portable Conductors** —

a. Must be made of two stranded conductors, each having a carrying capacity equivalent to not less than No. 14 B. & S. wire, and each covered with an approved insulation and covering.

Where not exposed to moisture or severe mechanical injury, each stranded conductor must have a solid insulation at least one-thirty-second of an inch in thickness, and must show an insulation resistance between conductors, and between either conductor and the ground, of at least one megohm per mile after one week's submersion in water at seventy degrees Fahrenheit and after three minutes' electrification, with 590 volts, and be protected by a slow-burning, tough-braided outer covering.

Where exposed to moisture and mechanical injury — as for use on decks, holds, and fire-rooms — each stranded conductor shall have a solid insulation to be approved, of at least one thirty-second of an inch in thickness and protected by a tough braid. The two conductors shall then be stranded together, using a jute filling. The whole shall then be covered with a layer of flax, either woven or braided, at least one-thirty-second of an inch in thickness, and treated with a non-inflammable waterproof compound. After one week's submersion in water at seventy degrees Fahrenheit, at 550 volts and a three minutes' electrification, must show an insulation between the two conductors, or between either conductor and the ground, of one megohm per mile.

71. **Bell or Other Wires** —

a. Shall never run in same duct with lighting or power wires.

72. **Table of Capacity of Wires** —

B. & S. G.	Area Actual C. M.	No. of Strands.	Size of Strands B. & S. G.	Amperes.
19	1,288	..	..	..
18	1,624	..	..	3
17	2,048	..	..	..
16	2,583	..	..	6
15	3,257	..	..	..
14	4,107	..	..	12
12	6,530	..	..	17
..	9,016	7	19	21
..	11,368	7	18	25
..	14,336	7	17	30
..	18,081	7	16	35
..	22,799	7	15	40
..	30,856	19	18	50
..	38,912	19	17	60
..	49,077	19	16	70
..	60,088	37	18	85
..	75,776	37	17	100
..	99,064	61	18	120
..	124,928	61	17	145
..	157,563	61	16	170
..	198,677	61	15	200
..	250,527	61	14	235
..	296,387	91	15	270
..	373,737	91	14	320
..	413,639	127	15	340

When greater conducting area than that of a single wire is required, the conductor shall be stranded in a series of 7, 19, 37, 61, 91, or 127 wires, as may be required; the strand consisting of one central wire, the remainder laid around it concentrically, each layer to be twisted in the opposite direction from the preceding.

73. **Switchboards** —

a. Must be made of non-combustible, non-absorptive insulating material, such as marble or slate.

b. Must be kept free from moisture, and must be located so as to be accessible from all sides.

c. Must have a main switch, main cutout and ammeter for each generator. Must also have a voltmeter and ground detector.

d. Must have a cutout and switch for each side of each circuit leading from board.

74. **Resistance Boxes** —

a. Must be made of non-combustible material.

b. Must be located on switchboard or away from combustible material. When not placed on switchboard they must be mounted on non-inflammable, non-absorptive insulating material.

c. Must be so constructed as to allow sufficient ventilation for the uses to which they are put.

75. **Switches** —

a. Must have non-combustible, non-absorptive insulating bases.

b. Must operate successfully at fifty per cent overload in amperes with twenty-five per cent excess voltage under the most severe conditions they are

liable to meet with in practice, and must be plainly marked, where they will always be visible, with the name of the maker and the current and voltage for which the switch is designed.

c. Must be double pole when circuits which they control supply more than six sixteen-candle-power lamps or their equivalent.

d. When exposed to dampness, they must be inclosed in a water-tight case.

76. **Cutouts** —

a. Must have non-combustible, non-absorptive insulating bases.

b. Must operate successfully, under the most severe conditions they are liable to meet with in practice, on short circuit with fuse rated at fifty per cent above, and with a voltage twenty-five per cent above the current and voltage they are designed for, and must be plainly marked, where they will always be visible, with the name of the maker and current and voltage for which the device is designed.

c. Must be placed at every point where a change is made in the size of the wire (unless the cutout in the larger wire will protect the smaller).

d. In places such as upper decks, holds, cargo spaces, and fire-rooms a water-tight and fireproof cutout may be used, connecting directly to mains when such cutout supplies circuits requiring not more than 660 watts energy.

e. When placed anywhere except on switchboards and certain places, as cargo spaces, holds, fire-rooms, etc., where it is impossible to run from center of distribution, they shall be in a cabinet lined with fire-resisting material.

f. Except for motors, searchlights, and diving-lamps shall be so placed that no group of lamps, requiring a current of more than six amperes, shall ultimately be dependent upon one cutout.

A single-pole covered cutout may be placed in the molding when same contains conductor supplying circuits requiring not more than 220 watts energy.

77. **Fixtures** —

a. Shall be mounted on blocks made from well-seasoned lumber treated with two coats of white lead or shellac.

b. Where exposed to dampness, the lamp must be surrounded by a vapor-proof globe.

c. Where exposed to mechanical injury, the lamp must be surrounded by a globe protected by a stout wire guard.

d. Shall be wired with same grade of insulation as portable conductors which are not exposed to moisture or mechanical injury.

78. **Sockets** —

a. No portion of the lamp socket or lamp base exposed to contact with outside objects shall be allowed to come into electrical contact with either of the conductors.

79. **Wooden Moldings** —

a. Must be made of well-seasoned lumber, and be treated inside and out with at least two coats of white lead or shellac.

b. Must be made of two pieces, a backing and a capping, so constructed as to thoroughly incase the wire, and provide a one-half inch tongue between the conductors, and a solid backing which, under grooves, shall not be less than three-eighths of an inch in thickness.

c. Where molding is run over rivets, beams, etc., a backing strip must first be put up and the molding secured to this.

d. Capping must be secured by brass screws.

80. **Motors** —

a. Must be wired under the same precautions as with a current of same volume and potential for lighting. The motor and resistance box must be protected by a double-pole cutout, and controlled by a double-pole switch, except in cases where one-quarter horse-power or less is used.

The leads or branch circuits should be designed to carry a current at least fifty per cent greater than that required by the rated capacity of the motor to provide for the inevitable overloading of the motor at times.

b. Must be thoroughly insulated. Where possible, should be set on base frames made from filled, hard, dry wood, and raised above surrounding deck. On hoists and winches they shall be insulated from bed-plates by hard rubber, fiber, or similar insulating material.

c. Shall be covered with a waterproof cover when not in use.

d. Must each be provided with a name-plate giving maker's name, the capacity in volts and amperes, and the normal speed in revolutions per minute.

GENERAL SUGGESTIONS.

In all electric work conductors, however well insulated, should always be treated as bare, to the end that under no conditions, existing or likely to exist, can a grounding or short circuit occur, and so that all leakage from conductor to conductor, or between conductor and ground, may be reduced to the minimum.

In all wiring special attention must be paid to the mechanical execution of the work. Careful and neat running, connecting, soldering, taping of conductors and securing and attaching of fittings, are specially conducive to security and efficiency, and will be strongly insisted on.

In laying out an installation, except for constant-current systems, the work should, if possible, be started from a center of distribution, and the switches and cutouts, controlling and connected with the several branches, be grouped together in a safe and easily accessible place, where they can be readily got at for attention or repairs. The load should be divided as evenly as possible among the branches, and all complicated and unnecessary wiring avoided.

The use of wire-ways for rendering concealed wiring permanently accessible is most heartily indorsed and recommended; and this method of accessible concealed construction is advised for general use.

Architects are urged, when drawing plans and specifications, to make provision for the channeling and pocketing of buildings for electric light or power wires, and in specifications for electric gas lighting to require a two-wire circuit, whether the building is to be wired for electric lighting or not, so that no part of the gas fixtures or gas-piping be allowed to be used for the gas-lighting circuit.

APPENDIX II.

REPORT OF THE COMMITTEE ON STANDARDIZATION.

[Accepted by the INSTITUTE, June 26, 1899.]

To the Council of The AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Gentlemen:

Your committee on Standardization begs to submit the following report, covering such subjects as have been deemed of pressing and immediate importance, and which are of such a nature that general agreement may be expected upon them.

While it is the opinion of the committee that many other matters might advantageously have been considered, as, for example, standard methods of testing: yet it has been deemed inexpedient to attempt to cover in a single report more than is here submitted.

Yours respectfully,

FRANCIS B. CROCKER, *Chairman.*
CARY T. HUTCHINSON.
A. E. KENNELLY.
JOHN W. LIEB, JR.
CHARLES P. STEINMETZ.
LEWIS B. STILLWELL.
ELIHU THOMSON.

GENERAL PLAN.

Efficiency. Sections 1 to 24

(I)	Commutating Machines,	Sections 6 to 11
(II)	Synchronous Machines,	" 10 to 11
(III)	Synchronous Commutating Machines,	" 12 to 15
(IV)	Rectifying Machines,	" 16 to 17
(V)	Stationary Induction Apparatus,	" 18 to 19
(VI)	Rotary Induction Apparatus,	" 20 to 23
(VII)	Transmission Lines,	" 24

Rise of Temperature. Sections 25 to 31.

Insulation. Sections 32 to 41.

Regulation. Sections 42 to 61.

Variation and Pulsation. Sections 62 to 65.

Rating. Sections 66 to 73.

Classification of Voltages and Frequencies. Sections 74 to 78.

Overload Capacities. Sections 79 to 82.

Appendices.
(I) Efficiency.
(II) Apparent Efficiency.
(III) Power Factor and Inductance Factor.
(IV) Notation.
(V) Table of Sparking Distances.

Electrical Apparatus will be treated under the following heads: —

I. **Commutating Machines,** which comprise a constant magnetic field, a closed-coil armature, and a multi-segmental commutator connected thereto.

Under this head may be classed the following: Direct-current generators; direct-current motors; direct-current boosters; motor-generators; dynamotors; converters and closed-coil arc machines.

A booster is a machine inserted in series in a circuit to change its voltage, and may be driven either by an electric motor, or otherwise. In the former case it is a motor-booster.

A motor-generator is a transforming device consisting of two machines; a motor and a generator, mechanically connected together.

A dynamotor is a transforming device combining both motor and generator action in one magnetic field, with two armatures or with an armature having two separate windings.

For converters, see III.

II. **Synchronous Machines,** which comprise a constant magnetic field, and an armature receiving or delivering alternating currents in synchronism with the motion of the machine; *i. e.*, having a frequency equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second.

III. **Synchronous Commutating Machines**: — These include: 1. Synchronous converters: i.e., converters from alternating to direct, or from direct to alternating current, and 2. Double-current generators; i.e., generators producing both direct and and alternating currents.

A converter is a rotary device transforming electric energy from one form into another without passing it through the intermediary form of mechanical energy.

A converter may be either:

a. A direct-current converter, converting from a direct current to a direct current or

b. A synchronous converter, formerly called a rotary converter, converting from an alternating to a direct current, or vice versa.

Phase converters are converters from an alternating-current system to an alternating-current system of the same frequency but different phase.

Frequency converters are converters from an alternating-current system of one frequency to an alternating-current system of another frequency, with or without changes of phase.

IV. **Rectifying Machines, or Pulsating-Current-Generators,** which produce a unidirectional current of periodically varying strength.

V. **Stationary Induction Apparatus**: i.e., stationary apparatus changing electric energy from one form into another, without passing it through an intermediary form of energy. These comprise:

a. Transformers, or stationary induction apparatus in which the primary and secondary windings are electrically insulated from each other.

b. Auto-transformers, formerly called compensators: i.e., stationary induction apparatus in which part of the primary winding is used as a secondary winding, or conversely.

c. Potential regulators, or stationary induction apparatus having a coil

in shunt, and a coil in series with the circuit, so arranged that the ratio of transformation between them is variable at will.

These may be divided into: —

1. Compensator potential-regulators, in which the number of turns of one of the coils is changed.

2. Induction potential-regulators, in which the relative positions of primary and secondary coils is changed.

3. Magneto potential-regulators, in which the direction of the magnetic flux with respect to the coils is changed.

d. Reactive coils, or reactance coils, formerly called choking coils: i.e., stationary induction apparatus used to produce impedance or phase displacement.

VI. Rotary Induction Apparatus, which consists of primary and secondary windings rotating with respect to each other. They comprise: —

a. Induction motors.

b. Induction generators.

c. Frequency changers.

d. Rotary phase converters.

EFFICIENCY.

1. The "efficiency" of an apparatus is the ratio of its net power output to its gross power input.*

2. Electric power should be measured at the terminals of the apparatus.

3. In determining the efficiency of alternating-current apparatus, the electric power should be measured when the current is in phase with the *E.M.F.*, unless otherwise specified, except when a definite phase difference is inherent in the apparatus, as in induction motors, etc.

4. Mechanical power in machines should be measured at the pulley, gearing, coupling, etc., thus excluding the loss of power in said pulley, gearing, or coupling, but including the bearing friction and windage. The magnitude of bearing friction and windage may be considered as independent of the load. The loss of power in the belt and the increase of bearing friction due to belt tension, should be excluded. Where, however, a machine is mounted upon the shaft of a prime mover, in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, should be excluded, owing to the practical impossibility of determining them satisfactorily. The brush friction, however, should be included.

a. Where a machine has auxiliary apparatus, such as an exciter, the power lost in the auxiliary apparatus should not be charged to the machine, but to the plant consisting of machine and auxiliary apparatus taken together. The plant efficiency in such cases should be distinguished from the machine efficiency.

5. The efficiency may be determined by measuring all the losses individually and adding their sum to the output to derive the input, or subtracting their sum from the input to derive the output. All losses should be measured at, or reduced to, the temperature assumed in continuous operation, or in operation under conditions specified. (See Sections 25 to 31.)

* An exception should be noted in the case of storage batteries or apparatus for storing energy, in which the efficiency, unless otherwise qualified, should be understood as the ratio of the energy output to the energy intake in a normal cycle.

In order to consider the application of the foregoing rules to various machines in general use, the latter may be conveniently divided into classes as follows: —

I. **Commutating Machines.** —

6. In commutating machines the losses are: —

a. Bearing friction and windage. (See Section 4.)

b. Molecular magnetic friction, and eddy currents in iron and copper. These losses should be determined with the machine on open circuit, and at a voltage equal to the rated voltage $+ Ir$ in a generator, and $- Ir$ in a motor, where I denotes the current strength, and r denotes the internal resistance of the machine. They should be measured at the correct speed and voltage, since they do not usually vary in proportion to the speed or to any definite power of the voltage.

c. Armature resistance losses, $I^2 r'$, where I is the current strength in the armature, and r' is the resistance between armature brushes, excluding the resistance of brushes and brush contacts.

d. Commutator brush friction.

e. Commutator brush-contact resistance. It is desirable to point out that with carbon brushes the losses (*d*) and (*e*) are usually considerable in low-voltage machines.

f. Field excitation. With separately excited fields, the loss of power in the resistance of the field coils alone should be considered. With shunt fields or series fields, however, the loss of power in the accompanying rheostat should also be included, the said rheostat being considered as an essential part of the machine, and not as separate auxiliary apparatus.

(*b*) and (*c*) are losses in the armature or "armature losses;" (*d*) and (*e*) "commutator losses;" (*f*) "field losses."

7. The difference between the total losses under load and the sum of the losses above specified, should be considered as "load losses" and are usually trivial in commutating machines of small field distortion. When the field distortion is large, as is shown by the necessity for shifting the brushes between no load and full load, or with variations of load, these load losses may be considerable, and should be taken into account. In this case the efficiency may be determined either by input and output measurements, or the load losses may be estimated by the method of Section II.

8. Boosters should be considered and treated like other direct-current machines in regard to losses.

9. In motor-generators, dynamotors, or converters, the efficiency is the

$$\frac{\text{electric output}}{\text{electric input}}.$$

II. **Synchronous Machines.** —

10. In synchronous machines the output or input should be measured with the current in phase with the terminal *E.M.F.*, except when otherwise expressly specified.

Owing to the uncertainty necessarily involved in the approximation of load losses, it is preferable, whenever possible, to determine the efficiency of synchronous machines, by input and output tests.

11. The losses in synchronous machines are:

a. Bearing friction and windage. (See Section 4.)

b. Molecular magnetic friction and eddy currents in iron, copper, and other metallic parts. These losses should be determined at open circuit of the machine at the rated speed and at the rated voltage, $+ Ir$ in a synchronous generator, $- Ir$ in a synchronous motor, where $I =$ current in armature, $r =$ armature resistance. It is undesirable to compute these losses from observations made at other speeds or voltages.

These losses may be determined either by driving the machine by a motor. or by running it as a synchronous motor, and adjusting its fields so as to get minimum current input and measuring the input by wattmeter. The former is the preferable method, and in polyphase machines the latter method is liable to give erroneous results in consequence of unequal distribution of currents in the different circuits caused by inequalities of the impedance of connecting leads, etc.

c. Armature-resistance loss, which may be expressed by $p I^2 r$; where $r =$ resistance of one armature circuit or branch, $I =$ the current in such armature circuit or branch, and $p =$ the number of armature circuits or branches.

d. Load losses as defined in Section 7. While these losses cannot well be determined individually, they may be considerable and, therefore, their joint influence should be determined by observation. This can be done by operating the machine on short circuit and at full-load current, that is, by determining what may be called the "short-circuit core loss." With the low field intensity and great lag of current existing in this case, the load losses are usually greatly exaggerated.

One-third of the short-circuit core loss may, as an approximation, and in the absence of more accurate information, be assumed as the load loss.

e. Collector-ring friction and contact resistance. These are generally negligible, except in machines of extremely low voltage.

f. Field excitation. In separately-excited machines, the $I^2 r$ of the field coils proper should be used. In self-exciting machines, however, the loss in the field rheostat should be included. (See Section 6*f*.)

III. **Synchronous Commutating Machines.** —

12. In synchronous converters, the power of the alternating-current side is to be measured with the current in phase with the terminal *E.M.F.*, unless otherwise specified.

13. In double-current generators, the efficiency of the machine should be determined as a direct-current generator in accordance with Section 6, and as an alternating-current generator in accordance with Section 11. The two values of efficiency may be different, and should be clearly distinguished.

14. In synchronous converters the losses should be determined when driving the machine by a motor. These losses are: —

a. Bearing friction and windage. (See Section 4.)

b. Molecular magnetic friction and eddy currents in iron, copper, and metallic parts. These losses should be determined at open circuit and at the rated terminal voltage, no allowance being made for the armature resistance, since the alternating and the direct currents flow in opposite directions.

c. Armature resistance. The loss in the armature is $q I^2 r$, where $I =$ direct current in armature, $r =$ armature resistance, and q a factor which is equal to 1.37 in single-phasers, 0.56 in three-phasers, 0.37 in quarter-phasers and 0.26 in six-phasers.

d. Load losses. The load losses should be determined in the same manner as described in Section 11 *d.*, with reference to the direct-current side.

e and *f.* Losses in commutator and collector friction and brush-contact resistance. (See Sections 6 and 11.)

g. Field excitation. In separately-excited fields, the $I^2 r$ loss in the field coils proper should be taken, while in shunt and series fields the rheostat loss should be included, except where fields and rheostats are intentionally modified to produce effects outside of the conversion of electric power, as for producing phase displacement for voltage control. In this case 25 per cent of the $I^2 r$ loss in the field proper at non-inductive alternating circuit should be added as proper estimated allowance for normal rheostat losses. (See Section 6*f.*)

15. Where two similar synchronous machines are available, their efficiency can be determined by operating one machine as a converter from direct to alternating, and the other as a converter from alternating to direct, connecting the alternating sides together, and measuring the difference between the direct-current input and the direct-current output. This process may be modified by returning the output of the second machine through two boosters into the first machine and measuring the losses. Another modification might be to supply the losses by an alternator between the two machines, using potential regulators.

IV. Rectifying Machines or Pulsating-Current Generators.—

16. These include: Open-coil arc machines, constant-current rectifiers, constant-potential rectifiers.

The losses in open-coil arc machines are essentially the same as in Sections 6 to 9 (closed-coil commutating machines.) In alternating-current rectifiers, however, the output must be measured by wattmeter and not by voltmeter and ammeter, since, owing to the pulsation of current and *E.M.F.*, a considerable discrepancy may exist between watts and volt amperes, amounting to as much as 10 or 15 per cent.

17. In constant-current rectifiers, transforming from constant-potential alternating to constant direct current by means of constant-current transformers and rectifying commutators, the losses in the transformers are to be included in the efficiency, and have to be measured when operating the rectifier, since in this case the losses are generally greater than when feeding an alternating secondary circuit. In constant-current transformers the load losses are usually larger than in constant-potential transformers, and thus should not be neglected.

The most satisfactory method of determining the efficiency in rectifiers is to measure electric input and electric output by wattmeter. The input is usually not non-inductive, owing to a considerable phase displacement and to wave distortion. For this reason the apparent efficiency should also be considered, since it is usually much lower than the true efficiency. The power consumed by the synchronous motor or other source driving the rectifier should be included in the electric input.

V. Stationary Induction Apparatus.—

18. Since the efficiency of induction apparatus depends upon the wave shape of *E.M.F.*, it should be referred to a sine wave of *E.M.F.*, except

expressly specified otherwise. The efficiency should be measured with non-inductive load, and at rated frequency, except where expressly specified otherwise. The losses are:

a. Molecular magnetic friction and eddy currents measured at open circuit and at rated voltage — Ir, where I = rated current, r = resistance of primary circuit.

b. Resistance losses, the sum of the $I^2 r$ of primary and of secondary in a transformer, or of the two sections of the coil in the compensator or auto-transformer, where I = current in the coil or section of coil, r = resistance.

c. Load losses, i.e., eddy currents in the iron and especially in the copper conductors, caused by the current. They should be measured by short-circuiting the secondary of the transformer and impressing upon the primary an *E.M.F.*, sufficient to send full-load current through the transformer. The loss in the transformer under these conditions measured by wattmeter gives the load losses + $I^2 r$ losses in both primary and secondary coils.

d. Losses due to the methods of cooling, as power consumed by the blower in air-blast transformers, and power consumed by the motor driving pumps in oil or water cooled transformers. Where the same cooling apparatus supplies a number of transformers, or is installed to supply future additions, allowance should be made therefor.

19. In potential regulators the efficiency should be taken at the maximum voltage for which the apparatus is designed, and with non-inductive load, unless otherwise specified.

VI. Rotary Induction Apparatus. —

20. Owing to the existence of load losses and since the magnetic density in the induction motor under load changes in a complex manner, the efficiency should be determined by measuring the electric input by wattmeter and the mechanical output at the pulley, gear, coupling, etc.

21. The efficiency should be determined at the rated frequency and the input measured with sine waves of impressed *E.M.F.*

22. The efficiency may be calculated from the apparent input, the power factor, and the power output. The same applies to induction generators. Since phase displacement is inherent in induction machines, their apparent efficiency is also important.

23. In frequency changers; i.e., apparatus transforming from a polyphase system to an alternating system of different frequency, with or without a change in the number of phases, and phase converters; i.e., apparatus converting from an alternating system, usually single phase, to another alternating system, usually polyphase, of the same frequency, the efficiency should also be determined by measuring both output and input.

VII. Transmission Lines. —

24. The efficiency of transmission lines should be measured with non-inductive load at the receiving end, with the rated receiving pressure and frequency, also with sinusoidal impressed *E.M.F.*'s., except where expressly specified otherwise, and with the exclusion of transformers or other apparatus at the ends of the line.

RISE OF TEMPERATURE.

General Principles. —

25. Under regular service conditions, the temperature of electrical machinery should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

26. The rise of temperature should be referred to the standard conditions of a room-temperature of 25° C., a barometric pressure of 760 mm. and normal conditions of ventilation; that is, the apparatus under test should neither be exposed to draught nor inclosed, except where expressly specified.

27. If the room temperature during the test differs from 25° C., the observed rise of temperature should be corrected by ½ per cent for each degree C.* Thus with a room temperature of 35° C., the observed rise of temperature has to be decreased by 5 per cent, and with a room temperature of 15° C., the observed rise of temperature has to be increased by 5 per cent. The thermometer indicating the room temperature should be screened from thermal radiation emitted by heated bodies, or from draughts of air. When it is impracticable to secure normal conditions of ventilation on account of an adjacent engine, or other sources of heat, the thermometer for measuring the air temperature should be placed so as fairly to indicate the temperature which the machine would have if it were idle, in order that the rise of temperature determined shall be that caused by the operation of the machine.

28. The temperature should be measured after a run of sufficient duration to reach practical constancy. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

In apparatus intended for intermittent service, as railway motors, starting rheostats, etc., the rise of temperature should be measured after a shorter time, depending upon the nature of the service, and should be specified.

In apparatus which by the nature of their service may be exposed to overload, as railway converters, and in very high voltage circuits, a smaller rise of temperature should be specified than in apparatus not liable to overloads or in low voltage apparatus. In apparatus built for conditions of limited space, as railway motors, a higher rise of temperature must be allowed.

29. In electrical conductors, the rise of temperature should be determined by their increase of resistance. For this purpose the resistance may be measured either by galvanometer test, or by drop-of-potential method. A temperature coefficient of 0.4 per cent per degree C. may be assumed for copper.† Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers.

30. It is recommended that the following maximum values of temperature elevation should not be exceeded:

* This correction is also intended to compensate, as nearly as is at present practicable, for the error involved in the assumption of a constant temperature coefficient of resistivity; i.e., 0.4 per cent degree C. taken with varying initial temperatures.

† By the formula $R_T = R_t(1 + 0.004\theta)$. Where R_t is the resistance at room temperature, R_T the resistance when heated, and θ the temperature elevation $(T - t)$ in degrees centigrade.

Commutating machines, rectifying machines, and synchronous machines.

Field and armature, by resistance, 50° C.

Commutator and collector rings and brushes, by thermometer, 55° C.

Bearings and other parts of machine, by thermometer, 40° C.

Rotary induction apparatus:

Electric circuits, 50° C., by resistance.

Bearings and other parts of the machine, 40° C., by thermometer.

In squirrel-cage or short-circuited armatures, 55° C., by thermometer, may be allowed.

Transformers for continuous service — electric circuits by resistance, 50° C., other parts by thermometer, 40° C., under conditions of normal ventilation.

Reactive coils, induction and magneto regulators — electric circuits by resistance, 55° C., other parts by thermometer, 45° C.

Where a thermometer, applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted. In using the thermometer, care should be taken so to protect its bulb as to prevent radiation from it, and, at the same time, not to interfere seriously with the normal radiation from the part to which it is applied.

31. In the case of apparatus intended for intermittent service, the temperature elevation which is attained at the end of the period corresponding to the term of full load should not exceed 50° C., by resistance in electric circuits. In the case of transformers intended for intermittent service, or not operating continuously at full load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevation above the surrounding air-temperature should not exceed 50° C. by resistance in electric circuits, and 40° C. by thermometer in other parts, after the period corresponding to the term of full load. In this instance, the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the full-load test may be taken as three hours, unless otherwise specified. In the case of railway, crane, and elevator motors, the conditions of service are necessarily so varied that no specific period corresponding to the full-load term can be stated.

INSULATION.

32. The ohmic resistance of the insulation is of secondary importance only, as compared with the dielectric strength, or resistance to rupture by high voltage.

Since the ohmic resistance of the insulation can be very greatly increased by baking, but the dielectric strength is liable to be weakened thereby, it is preferable to specify a high dielectric strength rather than a high insulation resistance. The high-voltage test for dielectric strength should always be applied.

Insulation Resistance. —

33. Insulation resistance tests should, if possible, be made at the pressure for which the apparatus is designed.

The insulation resistance of the complete apparatus must be such that the rated voltage of the apparatus will not send more than $\frac{1}{1000000}$ of the full-load

current, at the rated terminal voltage, through the insulation. Where the value found in this way exceeds 1 megohm, 1 megohm is sufficient.

Dielectric Strength. —

34. The dielectric strength or resistance to rupture should be determined by a continued application of an alternating *E.M.F.* for one minute. The source of alternating *E.M.F.* should be a transformer of such size that the charging current of the apparatus as a condenser does not exceed 25 per cent of the rated capacity of the transformer.

35. The high-voltage tests should not be applied when the insulation is low, owing to dirt or moisture, and should be applied before the machine is put into commercial service.

36. It should be pointed out that tests at high voltages considerably in excess of the normal voltages are admissible on new machines, to determine whether they fulfill their specifications, but should not be made subsequently at a voltage much exceeding the normal, as the actual insulation of the machine may be weakened by such tests.

37. The test for dielectric strength should be made with the completely assembled apparatus and not with its individual parts; and the voltage should be applied as follows: —

1st. Between electric circuits and surrounding conducting material; and,

2d. Between adjacent electric circuits, where such exist, as in transformers.

The tests should be made with a sine wave of *E.M.F.*, or where this is not available, at a voltage giving the same striking distance between needle points in air as a sine wave of the specified *E.M.F.*, except where expressly specified otherwise. As needles, new sewing-needles should be used. It is recommended to shunt the apparatus during the test by a spark gap of needle points set for a voltage exceeding the required voltage by 10 per cent.

A table of approximate sparking distances is given in Appendix V.

38. The following voltages are recommended for apparatus, not including transmission lines or switchboards:

Rated Terminal Voltage.	Capacity	Testing Voltage.
Not exceeding 400 volts	Under 10 *K. W.*	1000 volts.
" " "	10 *K. W.* and over	1500 "
400 and over, but less than 800 volts	Under 10 *K. W.*	1500 "
" " " "	10 *K. W.* and over	2000 "
800 " " 1200 "	Any	3500 "
1200 " " 2500 "	Any	5000 "
2500 "	Any	Double the normal rated voltages.

Synchronous motor fields and fields of converters started from the alternating current side . . . . 5000 volts.

Alternator field circuits should be tested under a breakdown test voltage corresponding to the rated voltage of the exciter, and referred to an output equal to the output of the alternator; i.e., the exciter should be rated for this test as having an output equal to that of the machine it excites.

Condensers should be tested at twice their rated voltage and at their rated frequency.

The values in the table above are effective values, or square roots of mean square reduced to a sine wave of *E.M.F.*

39. In testing insulation between different electric circuits, as between primary and secondary of transformers, the testing voltage must be chosen corresponding to the high-voltage circuit.

40. In transformers of from 10,000 volts to 20,000 volts, it should be considered as sufficient to operate the transformer at twice its rated voltage, by connecting first the one, and then the other terminal of the high-voltage winding to the core and to the low-voltage winding. The test of dielectric resist ance between the low-voltage winding and the core should be in accordance with the recommendation in Section 38 for similar voltages and capacities.

41. When machines or apparatus are to be operated in series, so as to employ the sum of their separate *E.M.F.*'s, the voltage should be referred to this sum, except where the frames of the machine are separately insulated both from ground and from each other.

REGULATION.

42. The term "regulation" should have the same meaning as the term "inherent regulation," at present frequently used.

43. The regulation of an apparatus intended for the generation of constant potential, constant current, constant speed, etc., is to be measured by the maximum variation of potential, current, speed, etc., occurring within the range from full load to no load, under such constant conditions of operation as give the required full-load values, the condition of full load being considered in all cases as the normal condition of operation.

44. The regulation of an apparatus intended for the generation of a potential, current, speed, etc., varying in a definite manner between full load and no load, is to be measured by the maximum variation of potential current, speed, etc., from the satisfied condition, under such constant conditions of operation as give the required full-load values.

If the manner in which the variation in potential, current, speed, etc., between full load and no load, is not specified, it should be assumed to be a simple linear relation, i.e., undergoing uniform variation between full load and no load.

The regulation of an apparatus may, therefore, differ according to its qualification for use. Thus the regulation of a compound-wound generator specified as a constant-potential generator will be different from that it possesses when specified as an over-compounded generator.

45. The regulation is given in percentage of the full-load value of potential, current, speed, etc.; and the apparatus should be steadily operated during the test under the same conditions as at full load.

46. The regulation of generators is to be determined at constant speed; of alternating apparatus at constant impressed frequency.

47. The regulation of a generator-unit, consisting of a generator united with a prime-mover, should be determined at constant conditions of the prime-mover; i.e., constant steam pressure, head, etc. It would include the inherent speed variations of the prime-mover. For this reason the regulation of a generator-unit is to be distinguished from the regulation of either the prime-mover, or of the generator contained in it, when taken separately.

48. In apparatus generating, transforming, or transmitting alternating cur-

rents, regulation should be understood to refer to non-inductive load; that is, to a load in which the current is in phase with the *E.M.F.* at the output side of the apparatus, except where expressly specified otherwise.

49. In alternating apparatus receiving electric power, regulation should refer to a sine wave of *E.M.F.*, except where expressly specified otherwise.

50. In commutating machines, rectifying machines, and synchronous machines, as direct-current generators and motors, alternating-current and polyphase generators, the regulation is to be determined under the following conditions:

a. At constant excitation in separately excited fields;

b. With constant resistance in shunt-field circuits; and

c. With constant resistances hunting series fields; i.e., the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

51. In constant potential machines, the regulation is the ratio of the maximum difference of terminal voltage from the rated full-load value (occurring within the range from full load to open circuit) to the full-load terminal voltage.

52. In constant-current machines, the regulation is the ratio of the maximum difference of current from the rated full-load value (occurring within the range from full load to short circuit) to the full-load current.

53. In constant-power machines, the regulation is the ratio of maximum difference of power from the rated full-load value (occurring within the range of operation specified) to the rated power.

54. In over-compounded machines, the regulation is the ratio of the maximum difference in voltage from a straight line connecting the no-load and full-load values of terminal voltage as function of the current to the full-load terminal voltage.

55. In constant-speed continuous-current motors, the regulation is the ratio of the maximum variation of speed from its full-load value (occurring within the range from full load to no load) to the full-load speed.

56. In transformers, the regulation is the ratio of the rise of secondary terminal voltage from full load to no load (at constant primary impressed terminal voltage) to the secondary terminal voltage.

57. In induction motors, the regulation is the ratio of the rise of speed from full load to no load (at constant impressed voltage), to the full-load speed.

The regulation of an induction motor is, therefore, not identical with the slip of the motor, which is the ratio of the drop in speed from synchronism to the synchronous speed.

58. In converters, dynamotors, motor generators, and frequency changers, the regulation is the ratio of the maximum difference of terminal voltage at the output side from the rated full-load voltage (at constant impressed voltage and at constant frequency) to the full-load voltage on the output side.

59. In transmission lines, feeders, etc., the regulation is the ratio of maximum voltage difference at the receiving end, between no-load and full non-inductive load, to the full-load voltage at the receiving end, with constant voltage impressed upon the sending end.

60. In steam engines, the regulation is the ratio of the maximum variation of speed in passing from full load to no load (at constant steam pressure at the throttle) to the full-load speed.

61. In a turbine or other water motor, the regulation is the ratio of the maximum variation of speed from full load to no load (at constant head of water; i.e., at constant difference of level between tail race and head race) to the full-load speed.

Variation and Pulsation. —

62. In prime-movers which do not give an absolutely uniform rate of rotation or speed, as in steam engines, the "variation" is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution as 360°; and the pulsation is the ratio of the maximum change of speed in an engine cycle to the average speed.

63. In alternators or alternating-current circuits in general, the variation is the maximum difference in phase of the generated wave of *E.M.F.* from a wave of absolutely constant frequency, expressed in degrees, and is due to the variation of the prime-mover. The pulsation is the ratio of the maximum change of frequency during an engine cycle to the average frequency.

64. If n = number of poles, the variation of an alternator is $\frac{n}{2}$ times the variation of its prime-mover if direct-connected, and $\frac{n}{2}\,p$ times the variation of the prime-mover if rigidly connected thereto in the velocity ratio p.

65. The pulsation of an alternating-current circuit is the same as the pulsation of the prime-mover of its alternator.

RATING.

66. Both electrical and mechanical power should be expressed in kilowatts, except when otherwise specified. Alternating-current apparatus should be rated in kilowatts on the basis of non-inductive condition; i.e., with the current in phase with the terminal voltage.

67. Thus the electric power generated by an alternating-current apparatus equals its rating only at a non-inductive load; that is, when the current is in phase with the terminal voltage.

68. Apparent power should be expressed in kilovolt-amperes as distinguished from real power in kilowatts.

69. If a power-factor other than 10 per cent is specified, the rating should be expressed in kilovolt-amperes and power-factor, at full load.

70. The full-load current of an electric generator is that current which with the rated full-load terminal voltage gives the rated kilowatts, but in alternating-current apparatus only at non-inductive load.

71. Thus in machines in which the full-load voltage differs from the no-load voltage, the full-load current should refer to the former.

If P = rating of an electric-generator and E = full-load terminal voltage, the full-load current is:

$I=\frac{P}{E}$ in a continuous-current machine or single-phase alternator.

$I=\frac{P}{E\sqrt{3}}$ in a three-phase alternator.

$I=\frac{P}{2E}$ in a quarter-phase alternator.

72. Constant-current machines, such as series arc-light generators, should be rated in kilowatts based on terminal volts and amperes at full load.

73. The rating of a fuse or circuit breaker should be the current strength at which it will open the circuit, and not the working-current strength.

Classification of Voltages and Frequencies. —

74. In direct-current, low-tension generators, the following average terminal voltages are in general use and are recommended:

125 volts. 250 volts. 550 volts.

75. In direct-current, and alternating-current, low-pressure circuits, the following average terminal voltages are in general use and are recommended:

110 volts. 220 volts.

In direct-current power circuits, for railway and other service, 500 volts may be considered as standard.

76. In alternating-current, high-pressure circuits at the receiving end, the following pressures are in general use, and are recommended:

1000 volts. 2000 volts. 3000 volts. 6000 volts.
10000 volts. 15000 volts. 20000 volts.

77. In alternating-current, high-pressure generators or generating systems the following terminal voltages are in general use, and are recommended:

1150 volts. 2300 volts. 3450 volts.

These pressures allow of a maximum drop in transmission of 15 per cent of the pressure at the receiving end. If the drop required is greater than 15 per cent, the generator should be considered as special.

78. In alternating-current circuits, the following approximate frequencies are recommended as desirable:

25 ~ or 30 ~ 40 ~ 60~ 120 ~ (*)

These frequencies are already in extensive use, and it is deemed advisable to adhere to them as closely as possible.

Overload Capacities. —

79. All guaranties on heating, regulation, sparking, etc., should apply to the rated load, except where expressly specified otherwise, and in alternating-current apparatus to the current in phase with the terminal *E.M.F.*, except where a phase displacement is inherent in the apparatus.

80. All apparatus should be able to carry a reasonable overload without self-destruction by heating, sparking, mechanical weakness, etc., and with an increase of temperature elevation not exceeding 15° C. above those specified for full loads. (See Sections 25 to 31.)

81. Overload guaranties should refer to normal conditions of operation regarding speed, frequency, voltage, etc., and to non-inductive conditions in alternating apparatus, except where a phase displacement is inherent in the apparatus.

82. The following overload capacities are recommended:

1st. In direct-current generators and alternating-current generators: 25 per cent for one-half hour.

2d. In direct-current motors and synchronous motors: 25 per cent for one-half hour, 50 per cent for one minute; except in railway motors and other apparatus intended for intermittent service.

* The frequency of 120 ~ may be considered as covering the already existing commercial frequencies between 120 ~ and 140 ~, and the frequency of 60 ~ as covering the already existing commercial frequencies between 60 ~ and ~ 70.

3d. Induction motors: 25 per cent for one-half hour, 50 per cent for one minute.

4th. Synchronous converters: 50 per cent for one-half hour.

5th. Transformers: 25 per cent for one-half hour; except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guaranties shall apply for the transformers as for the apparatus connected thereto.

6th. Exciters of alternators and other synchronous machines, 10 per cent more overload than is required for the excitation of the synchronous machine at its guaranteed overload and for the same period of time.

APPENDIX I.

EFFICIENCY.

Efficiency of Phase-Displacing Apparatus. —

In apparatus producing phase displacement, as, for example, synchronous compensators, exciters of induction generators, reactive coils, condensers, olarization cells, etc., the efficiency should be understood to be the ratio of the volt-ampere activity to the volt-ampere activity plus power loss.

The efficiency may be calculated by determining the losses individually, adding to them the volt-ampere activity, and then dividing the volt-ampere activity by the sum.

1st. In synchronous compensators and exciters of induction generators, the determination of losses is the same as in other synchronous machines under Sections 10 and 11.

2d. In reactive coils the losses are molecular friction, eddy losses, and $I^2 r$ loss. They should be measured by wattmeter. The efficiency of reactive coils should be determined with a sine wave of impressed *E.M.F.*, except where expressly specified otherwise.

3d. In condensers, the losses are due to dielectric hysteresis and leakage, and should be determined by wattmeter with a sine wave of *E.M.F.*

4th. In polarization cells, the losses are those due to electric resistivity and a loss in the electrolyte of the nature of chemical hysteresis, and are usually very considerable. They depend upon the frequency, voltage, and temperature, and should be determined with a sine wave of impressed *E.M.F.*, except where expressly specified otherwise.

APPENDIX II.

Apparent Efficiency. —

In apparatus in which a phase displacement is inherent to their operation, apparent efficiency should be understood as the ratio of net power output to volt-ampere input.

Such apparatus comprise induction motors, reactive synchronous converters, synchronous converters controlling the voltage of an alternating-current system, self-exciting synchronous motors, potential regulators, and open magnetic circuit transformers, etc.

Since the apparent efficiency of apparatus generating electric power depends upon the power factor of the load, the apparent efficiency, unless otherwise specified, should be referred to a load power-factor of unity.

APPENDIX III.

Power Factor and Inductance Factor. —

The power factor in alternating circuits or apparatus may be defined as the ratio of the electric power, in watts, to volt-amperes.

The inductance factor is to be considered as the ratio of wattless volt-amperes to total volt-amperes.

Thus, if p = power factor, q = inductance factor,

$$p^2 + q^2 = 1.$$

The power factor is the $\frac{\text{(energy component of current or } E.M.F.)}{\text{(total current or } E.M.F.}$

and the inductance factor is the

$$\frac{\text{(wattless component of current or } E.M.F.}{\text{(total current or } E.M.F.,} = \frac{\text{true power.}}{\text{volt amperes.}}$$

Since the power-factor of apparatus supplying electric power depends upon the power-factor of the load, the power-factor of the load should be considered as unity, unless otherwise specified.

APPENDIX IV.

The following notation is recommended: —

E, e, voltage, $E.M.F.$, potential difference.
I, i, current.
P, power.
Φ, magnetic flux.
$\mathcal{B}$, magnetic density.
R, r, resistance.
X, x, reactance.
Z, z, impedance.
L, l, inductance.
C, c, capacity.
Vector quantities when used should be denoted by capital italics.

APPENDIX V.

Table of Sparking Distances in Air between Opposed Sharp Needle-Points, for Various Effective Sinusoidal Voltages, in inches and in centimeters.

Kilovolts Sq. Root of Mean Square.	Distance.		Kilovolts Sq. Root of Mean Square.	Distance	
	Inches.	Cms.		Inches.	Cms.
5	0.225	0.57	60	4.65	11.8
10	0.47	1.19	70	5.85	14.9
15	0.725	1.84	80	7.1	18.0
20	1.0	2.54	90	8.35	21.2
25	1.3	3.3	100	9.6	24.4
30	1.625	4.1	110	10.75	27.3
35	2.0	5.1	120	11.85	30.1
40	2.45	6.2	130	12.95	32.9
45	2.95	7.5	140	13.95	35.4
50	3.55	9.0	150	15.0	38.1

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